INTRODUCTION

TO

PETROFABRIC ANALYSIS

By

H. W. FAIRBAIRN

1935

INTRODUCTION

to

PETROFABRIC ANALYSIS

by

H. W. FAIRBAIRN

Issued by

Dept. of Geology, Queen's University, Kingston, Canada

1 9 3 5

SUPPLEMENT

Note 1

The presentation of these notes in mimeograph form at the present time is primarily with the intention of inviting criticism and having attention called to errors of omission and commission. The writer would therefore appreciate suggestions and be glad to hear of other points of view.

Note 2.

Since completion of the manuscript the term "Structural Petrology" has been proposed by E. B. Knopf as a substitute for "Petrofabric Analysis". The former has an advantage in that it carries the suggestion of combined field and microscopic study of structures, and contrasts sharply with "Chemical Petrology". "Structural Geology" is ordinarily used in connection with field structures, while "Petrofabric Analysis" conveys to most uninitiated readers a conception of microscopic study only. "Structural Petrology" avoids the apparent shortcomings of these two terms.

Note 1.

The presentation of these notes in mimeographed form at the present time is primarily with the intention of inviting criticism and having attention called to errors of omission and commission. The writer would therefore appreciate suggestions and be glad to hear of other points of view.

Note 2.

Since completion of the manuscript the term "Structural Petrology" has been proposed by E. B. Knopf as a substitute for "Petrofabric Analysis". The former has the advantage in that it carries the suggestion of combined field and microscopic study of structures, and associates closely with "Chemical Petrology", "Structural Geology" [illegible] structures, while "Petrofabric Analysis" conveys at least to uninitiated readers a connotation of microscopic study only. "Structural Petrology" avoids the apparent shortcomings of these two terms.

-- C O N T E N T S --

INTRODUCTION TO PETROFABRIC ANALYSIS

Introduction and Acknowledgments

Petrofabric analysis is a study of the spatial relations of minerals, joints, cleavages, etc., in their natural occurrence in rocks. It concerns in brief the spatial physical data of rocks, in contrast to the chemical data. In America the first important contribution to this field was Leith's "Rock Cleavage" (L1), published in 1905. Since that time two Austrian investigators, Sander and Schmidt, with their co-workers, have amplified the earlier conceptions and with the aid of improved methods of analysis have made important contributions to this field. Unfortunately, American investigators as a whole have not kept abreast of this European work and only recently has any interest been aroused in it. The reasons for this condition are to be found in our deficient knowledge of the German language, in our mental opposition to the considerable body of new terms used, in the tediousness of the analyses, and lastly in our pre-occupation with problems of an economic and reconnaissance nature. The writer recently had opportunity to study with considerable thoroughness the work of the European investigators and is convinced that we cannot afford longer to neglect their contributions.

INTRODUCTION TO PETROFABRIC ANALYSIS

Introduction and Acknowledgments

Petrofabric analysis is a study of the spatial relations of minerals, joints, cleavages, etc., to their natural occurrence in rocks. It concerns in brief the spatial physical data of rocks, in contrast to the chemical data. In America the first important contribution to this field was Leith's "Rock Cleavage," published in 1905. Since that time two Austrian investigators, Sander and Schmidt, with their co-workers, have amplified the earlier conceptions and with the aid of improved methods of analysis have made important contributions to this field. Unfortunately American investigators as a whole have not kept abreast of this European work and only recently has any interest been aroused in it. The reasons for this condition are to be found in an insufficient knowledge of the German language, in our natural opposition to the considerable body of new terms used, in the tediousness of the analyses, and lastly in our pre-occupation with problems of an economic and reconnaissance nature. The writer recently had opportunity to study with considerable thoroughness the work of the European investigators and is convinced that we cannot afford longer to neglect their contributions.

The following notes are based on a series of lectures given by the writer at Queen's University in 1934-35 and their publication is intended to make the data of petrofabric analysis available to a wider circle, especially to those to whom the fundamental German literature is largely unknown.

No claim is made to originality of presentation in the following pages. The entire basis of the work is to be found in Sander's "Gefügekunde der Gesteine" (L 2) which, despite the difficulties it offers to a beginner, is a monument to years of painstaking investigation and constructive thought on the part of its author. Although no misrepresentation of Sander's data and ideas is intended in these notes, the writer assumes full responsibility for any discrepancies which may appear. Stress is naturally laid on features of particular interest to American investigators with the idea of relating to current conceptions the conclusions drawn from petrofabric analysis.

The writer acknowledges his indebtedness to Professor Sander and his co-workers in Innsbruck, Doctors Schmidegg, Felkel, and Ladurner, for their unselfish assistance during his two-year apprenticeship in their department; to Doctor Laves of Göttingen for introductory work in X-ray analysis; to Professor Schmidt of Berlin for numerous discussions of petrofabric problems. The two years of study in Europe were made possible through a Travelling Fellowship granted by the Royal Society of Canada.

The work at Queen's University was made possible through the initiative of Professor M. B. Baker, and he and Dr. J. F. Henderson have kindly read the manuscript. Mr. W. C. Güssow has drawn the figures. Professors Bruce, Hawley, and

Rose have made many helpful suggestions during the lecture course. To all of these the writer expresses his thanks. Shortcomings in the notes, which will become apparent as time passes, can be corrected with supplementary sheets, since it is not the intention to suggest to the reader that the last word has been said on either data or interpretation as presented here.

Previous papers in English on various general and detailed phases of petrofabric analysis are listed under L.1,3,4,5. These notes will supplement them in some respects and it is hoped that by study of them all a still more complete picture of the methods and aims of this work will emerge.

Elementary Considerations and Definitions

The description and interpretation of the data of this spatial mineralogy requires the introduction of a considerable number of unfamiliar terms. These have been in common use for many years in Austria and Germany and the writer does not apologize for adopting them. In most cases equivalent expressions are lacking in our current English terminology and those used in the following pages are not necessarily the best expression of the German terms. In cases in which a suitable English equivalent has not been found the German term is retained for the present.

The study of minerals as petrofabrics does not involve new idea so much as a more accurate re-orientation of existing ones, together with a broadening of our conceptions and hypotheses. When, therefore, the basis of petrofabric work is once

mastered, the reader will begin to realize the scope of this type of analysis and appreciate the preciseness of definition made possible by Sander and Schmidt. Instead of working from the "outside in", as in field geology, the process is reversed as far as possible and the investigation is made from the "inside out".

Petrofabric analysis is a study of the fabric of rocks. This term, first used by E. B. Knopf (L 3) as an equivalent of the German term "Gefuge" is defined by Sander as follows - "The spatial data in the interior of a structure, having any exterior shape or boundaries, describe the fabric of the structure." A literal translation of "Gefüge" would be "Textur" or "Struktur", but, as is well-known, "Textur" means structure in English and vice versa. It is therefore in the interest of accuracy to use a neutral term. As far as the writer is aware "fabric" has been introduced only once before into geologic terminology and is defined as the "shape and arrangement of the crystalline and non-crystalline parts of a structure." It forms part of the C.I.P.W. classification which divides textures according to their crystallinity, granularity and fabric. (L 6) Comparison of this definition with the one above indicates that there is no conflict in use, but the C.I.P.W. fabric is restricted to <u>visible</u> shapes and arrangement while in its broader meaning <u>all</u> spatial data, internal and external, are ascribed to the fabric. Moreover, the C.I.P.W. "fabric" is not in common use at the present time so that its extension to the field of spatial mineralogy does not raise any problem in terminology.

As defined, the study of fabrics is not limited to rock structures. All natural and artificial structures have a fabric in the same sense and the study of metal fabric, for example, is of particular importance. We confine ourselves here however to rock fabrics or petro-fabrics.

Genetically, there are two types of petrofabrics to be distinguished, (I) Deformation fabrics and (2) Apposition fabrics. A deformation fabric is one whose elements owe their present position to movements resulting from either differential (rotational) or non-differential (non-rotational) stress. An apposition fabric is one which owes its origin to either growth of the elements in place (growth fabric) or to primary deposition from a flowing or a non-flowing medium. These condensed statements require expansion. In the first definition a fabric element is a single crystal or group of crystals which behaves as a unit under the molecular or mechanical forces acting on a structure. Differential stress indicates that the chief stress is applied in a direction inclined to the direction of shortening of the structure. (see also p. 40) Non-differential stress indicates that the chief stress is applied parallel to the direction of shortening of the structure.

The second definition is self-explanatory. Apposition, first used by Sander (L 4) as an equivalent for the German term "Anlagerung" means "the placing beside each other" of the elements and all primary structures (depositional fabrics) and crystal growth fabrics come under this group.

This grouping of rock fabrics as "deformation" or "apposition" is fundamental. A deformation fabric is character-

istic of most of the metamorphic rocks and also of some types of igneous and sedimentary rocks in which megascopic evidence of deformation is lacking. Apposition fabrics include all other sedimentary and igneous rocks from which no evidence of deformation is obtainable. This group has been less studied and will therefore receive less attention than the more complicated deformation fabrics.

A fabric is said to be isotropic or anisotropic in the same sense as in optics. The isotropic state is illustrated in the case in which the elements of a fabric are arranged at random and with no one position, either crystallographic or dimensional, favoured. The antisotropic state is much the commoner and its study forms the basis of petrofabric analysis. The most useful method is a statistical, grain-by-grain survey of a fabric by means of a Universal stage. If it turns out to be anisotropic, as is usual, we speak of its orientation. Expressed in definition--The statistically anisotropic arrangement of the elements in a fabric defines its orientation. We speak further of the orientation process by which a statistically anisotropic arrangement of the elements is brought about.

The orientation process may be passive or active as far as the behaviour of the elements is concerned. A passive orientation process is defined as one in which only external mechanical forces act to bring the fabric elements into their present positions. It is characteristic of deformation and depositional fabrics; the elements take no active part in the process and are merely the victims of the applied forces. An active orientation process, on the other hand, is characteristic of those apposition

fabrics in which crystal growth occurs. Only molecular forces are at work here and they alone produce the orientation.

Two types of orientation result from active and passive processes - (I) a lattice orientation and (2) a dimensional orientation. A lattice orientation is formed in the case in which the orientation process affects only the internal space lattice structure of the elements. It may be active or passive. A dimensional orientation is formed in the case in which the orientation process affects only the external shapes of the elements. This can be only a passive orientation process.

With these basic ideas as a framework we pass now to a survey of the methods of investigation before considering the analyses in more detail.

METHODS

The following pages include the published information together with a number of minor details of technique which have been found useful. The methods are grouped as follows--

A. Selection of Material

B. Optical Methods for Non-Opaque Material

   1. Preparation
   2. Examination
      (a) Ordinary Microscope
      (b) Universal Stage
      (c) Oblique Incident Light
   3. Contouring and Rotation of Diagrams

C. Optical Methods for Opaque Material

D. X-ray Methods

E. Useful Chemical Tests

No detail of elementary petrographic or X-ray practice is given as it is obvious that the student must be familiar with such before attempting the special applications for petrofabric analysis. Since the optical methods for non-opaque material are best known and most useful they receive the most attention here. The experience of the Innsbruck Mineralogy department serves as a basis for most of the detail presented and the writer is greatly indebted to Professor Sander and his co-workers for their co-operation.

A. SELECTION OF MATERIAL

The selection of material for petrofabric analysis depends in the first and last analysis on the experience of the collector. Specimens may be taken with two objects in view, (1) in order to study in detail some uninvestigated feature of the grain-fabric or (2) systematically over an area so as to obtain the maximum information regarding the structural history of the region. Under (1) a beginner, unfamiliar with investigations previously made, will duplicate much work and at the same time pass by much valuable material. It is a good fault, however, to collect too much rather than too little. Under (2) the field relations must serve as a guide.

The method of collecting is simple. Select a place on the outcrop and break off a piece of suitable size. Before attempting to trim it fit it back into place in the outcrop. Then determine the strike of a schistosity, bedding or joint plane present in the specimen and, holding the compass in the

strike direction, draw this direction with coloured pencil on the specimen, using the straight edge of the compass as ruler. If it is not practicable to use a pencil (due to the specimen being wet or too rough) an instrument such as a dental pick will be found very useful to scratch in the direction. Then draw the dip at right angles to this line and number the specimen, recording the strike and dip in the notebook opposite this number. The geographic directions are thus established permanently for the specimen and may after analysis be correlated with fabric directions. In the laboratory it is advisable to mark the strike, dip and number with India ink or paint in order to make the record more permanent.

B. OPTICAL METHODS FOR NON-OPAQUE MATERIAL

The study of non-opaque minerals optically has furnished to date the greatest part of our information concerning rock fabrics and will probably continue to do so. These methods are treated in more detail than the others as they are the best developed and form the basis of the subject.

1. Preparation

Thin sections are ordinarily cut $\perp$ to any planes or directions visible in the specimens (not geographical directions.) If the material is absolutely massive only a geographically oriented section can be made. For ordinary work one section suffices; for more detailed work two and even three, perpendic-

ular to each other, may be necessary. The specimen is first sawn parallel to the direction in which sections are required, an arrow is then drawn on the ground surface either parallel or perpendicular to a direction visible in the surface and the surface marked with one of the three conventional fabric axes, 'a', 'b' or 'c'. (See p. 32) A rough drawing of the specimen is also made so that, if during preparation of the section it is broken to any extent, its orientation may still be recognized. The thin-section maker must now fulfill the following conditions- (1) The ground surface of the specimen must be the surface which is glued to the object glass. (2) If a direction shows in the section it is to be placed parallel to one of the edges of the object glass. (3) The arrow on the ground surface of the specimen is to be transferred with a diamond point to the object glass in parallel position; also the number of the specimen and of the surface. (4) The marks on the specimen are to be retained as far as possible and the entire remaining specimen is to be preserved. Adherence to these rules will prevent errors in orientation and thereby save much time and labour.

2. Examination

(a) With Petrographic Microscope -

Before undertaking a statistical examination with the Universal stage a routine examination of the section is necessary. The mineral composition, grain size and shape, visible structures, textures and directions must be noted so that one can plan to best advantage the Universal stage work to follow.

Many sections will give evidence of orientation of optic directions by simple tests. For uniaxial minerals, in which the optic axis is parallel to the vertical axis, this information is of value as it gives evidence of orientation of a crystallographic direction. The following three tests are possible - (1) The calcite grains of a calcareous marble or schist may show a concentration of low indices in one position under polarized light (analyzer out) and after 90° rotation a concentration of high indices. This test is only possible, however, with a mineral of high birefringence. (2) With crossed nicols a majority of grains of one mineral may extinguish or become illuminated within a few degrees rotation of the stage. (3) With a quartz wedge, mica plate, or gypsum plate one obtains indications of orientation more commonly than with tests (1) and (2). The gypsum plate test is particularly useful with quartz, the mineral most often analysed with the U-stage, and Pernt (L 7) has worked out the degree of freedom which γ (or ε) possesses in relation to the γ' (or ε') shown by the test. Thus if a grain upon testing is blue in the schistosity direction, γ may lie anywhere in a broad zone sub-parallel to the schistosity (but nowhere exceeding 45° on either side of the schistosity.) If the grain shows yellow in the schistosity direction γ lies in a zone sub-normal to the schistosity which is smaller than that for the case $\gamma' \parallel$ schistosity. Thus the γ' test has a different value for the two directions parallel or perpendicular to schistosity, the degree of freedom for γ being greater when γ' (blue colour) lies parallel to schistosity. For details see Pernt's analysis.

If a Universal stage is not available for further analysis one may obtain evidence of the degree of orientation in the schistosity by making another slide $\perp$ schistosity (but not parallel to the first) and comparing the abundance of isotropic sections of quartz appearing in each. Also, in making estimates of the approximate position of γ' it is useful to raise the microscope tube just enough to throw the grains out of focus. By so doing one often obtains indications of the position of γ which escape notice when the section is in exact focus.

For biaxials (orthorhombic excepted) the less direct connection between optic and crystallographic directions renders gypsum plate tests less useful. The optic and crystallographic directions in triclinic minerals have no fixed relations one with another; in monoclinic minerals one of the three optic symmetry planes coincides with a crystallographic plane. Only in orthorhombic minerals do the optic and crystallographic directions coincide. Gypsum plate tests on sections $\perp$ schistosity give the following general information for biaxials concerning orientation of the optic directions (where γ' represents the range of blue upon rotation of the stage, 'd' is the intersection line of the schistosity plane and the plane of the thin section, α, β, γ are the indices, 2V is the optic angle.)

(a) If $\gamma' \perp d$ probably γ is approximately $\perp$ schistosity.

(b) If $\gamma' \parallel d$ probably α is approximately $\perp$ schistosity.

From the above the probability is that a minority of axial planes (which contain both α and γ) lie in the plane of schistosity. This probability, however is dependent on two factors, the sign

of the mineral and the size of the optic angle. Thus for (a) an increasing number of axial planes lie in the schistosity if the mineral is negative. As $2V \rightarrow 0$ this is emphasized. For (b) an increasing number of axial planes lie in the schistosity if the mineral is positive, a further increase occurring as $2V \rightarrow 0$. The degree of probability of (a) and (b) must therefore be worked out for each individual mineral, and if a positive result is obtained (evidence of optic orientation only) this information must be converted to terms of crystallographic direction. Without subsequent Universal stage analysis it is obvious that no very definite idea of the orientation can be obtained by this method.

The Berek Compensator has been found useful in making rapid approximations of the orientation of mica. By suitable rotation of the plate, γ' is quickly determined for each grain and allows an estimation of the degree of orientation.

(b) Universal Stage

Precise data concerning the fabric of a thin section are obtained by measuring the positions of all optic and crystallographic directions and planes with a Universal stage and plotting their relative positions on a standard equal-area projection. Any petrographic microscope to which a stage may be attached may be used. The first Universal stage of Federow was too small for this work and not until the larger model of Berek appeared was it possible to make statistical analyses of thin sections. In 1925 Schmidt (L 8) published the results of the first measurements made in this way.

Among the Universal stages at present available, the model by Fuess (Fig. 1) is the most satisfactory for this statistical work as the diameter of the inner stage on which the section rests is about 15% greater than that of the others, thus allowing more freedom of movement of the section. Formerly it was often necessary to break off the corners of the section in order to measure all of the grains because of interference with the fittings of the stage. A Schmidt parallel ruler is clamped to one arm of the upper hemisphere so that the section may be moved at will in parallel position across the field of view. In order to use the enlarged inner stage of the Fuess model to best advantage, the arms of the upper hemisphere are mounted eccentrically, and the ruler (with the section) has as a result much greater freedom of movement $\perp$ to the hemisphere arms than when they are mounted opposite one another. A second Fuess Universal stage recently developed by Drescher (L 9) is intended for analysis of very coarse fabrics. Sections of 25 sq. cm. may be measured, with the result that a fabric such as graphic granite can be measured as easily as a fine-grained schist. The apparatus, however, is not yet perfected and is still being improved.

The adjustment of the Universal stage axes is made as follows - With the two horizontal axes at 0° place a particle of dust at the intersection of the cross-hairs and rotate on the inner stage. Loosen the Universal stage set screws at the base of the frame, tap gently in the required direction and test on the inner stage until finally the dust particle does not move from the intersection upon rotation. Then rotate on one of the horizontal axes (the other still at 0°) and turn the <u>microscope</u>

stage sufficiently so that the dust particle remains exactly parallel with the cross-hair upon testing with the horizontal axis. Clamp the microscope stage in this position and test the accuracy of the adjustment on the other horizontal axis.

To mount a section one places it (cover-glass up) on the stage, clamping it in place so that one edge is held firmly against the ruler. Screw the adjustable glass plate (on which the section rests) in such position that a grain at the cross-hair intersection in the 0° position remains there for all positions of the horizontal axes. Vaseline oil or any thin, chemically inactive oil makes a very satisfactory immersion medium and a section may be left on the stage indefinitely without necessity of renewing the oil surface. The section is moved systematically back and forth in parallel position with the ruler until the measurements desired have been made. Hemispheres must be used whose indices do not vary too greatly from those of the mineral species being measured.

The data are recorded on an equal-area projection. This is a projection adapted from the cartographer in which e.g. polar regions are shown in their true proportions. The stereographic projection commonly used in crystallography is greatly distorted at angles greater than 50° from the centre, and is therefore objectionable in petrofabric work. The projection may be mounted on a turntable such as that of Leitz and covered with a sheet of transparent paper to record the data. An equally satisfactory and less expensive apparatus is made as follows - Lay an equal-area projection blank on a square board of suitable size and tack a piece of thick transparent celluloid

over both. Make a hole in the exact centre of the projection and lay a circular piece of thin transparent paper on the celluloid. Inscribe a circle on the paper of the same radius as the projection and put a small piece of strong transparent adhesive plaster at its exact centre. As a reference mark draw a small arrow anywhere normal to the inscribed circle and orient the board so that its graduation is in parallel position with that of the inner stage.

The actual plotting is similar to that used with the stereographic projection except that one plots the projection of the points on the lower half of the theoretical sphere, not on the upper half. Therefore when one rotates the stage north about the east-west axis one plots the reading north from the middle point of the projection, not south as in the other method. Schmidt first used this, and for comparison of diagrams it is advisable to retain it in future. It has the advantage that the direction of rotation of the stage axes is the same as the direction in which one plots the reading.

For calcite a modification of the projection is necessary. (Fig. 2) Due to its abnormally high birefringence the disparity in index between the hemisphere (1.64) and ε is appreciable and a correction must be made. For ω none is necessary for angles less than 50° , as the hemisphere is close enough to it in index. The correction for ε is large, 60° on the uncorrected projection being almost 10° too great.

<u>Measurement of Uniaxials</u> (e.g. To find the optic axis of calcite)

<u>Note</u>: The writer follows Winchell's nomenclature for the Universal stage --

EW - east-west horizontal axis
NS - north-south horizontal axis
IS - inner stage on which the section rests
MS - microscope stage
OSP - optic symmetry plane

1. Set EW and NS axes at 0°. Focus on grains in immediate vicinity of the cross-hairs. 2. Select a grain for measurement and turn it on IS until it is dark. 3. Test the extinction by rotation on NS. If the grain does not remain dark, rotate 90° on IS and test the extinction as before. (Neglect the "flash" extinction which is common in calcite.) In this position it will remain dark since this is a plane containing the optic axis. 4. Turn on EW a few degrees and then rotate on NS. Three cases are now possible as follows - (A) There will be a sharply defined extinction. The grain will be yellowish a degree or so on either side of this position (gray with quartz.) This indicates $\mathcal{E}$, the low index. Rotate on EW back to the zero position and the optic axis now coincides with the axis of the microscope. To test this rotate on MS and the grain will remain dark. The angles read on the IS and NS scales define ω and therefore the optic axis. (B) There will be a poorly defined extinction. In this case adjust the amount of rotation on EW so that the most accurate position of extinction may be determined. The plane now lying parallel to NS is the plane in which ω vibrates and is the measure of $\mathcal{E}$. Rotate on EW back to 0°

and then rotate on MS. The grain becomes illuminated, proving that the optic axis does not lie in the axis of the microscope. Read off the angles on IS and NS and plot the pole to this plane. This pole is the optic axis of the grain. (C) Both (A) and (B) may appear. In this case select (A) if the angle on NS is not greater than 50°. (This is because the error arising due to the variation between ω and the index of the hemisphere becomes appreciable at angles greater than 50°.) If greater than 50° measure ε as in (B). After a little practice the sharp extinction (denoting the optic axis) and the less sharp extinction (denoting the plane $\perp$ to the axis) can be easily distinguished.

<u>Measurement of Biaxials</u> (Determination of OSP and the Indicatrix) Bring EW and NS to 0°. That extinction direction which shows less illumination on rotation is made parallel with the NS cross-hair by rotation on IS. Rotate on NS a few degrees and restore the extinction by suitable rotation on IS. Two cases now arise- (A) Rotate on EW. If the grain now remains more nearly at extinction than before repeat the above process of rotating a few degrees on NS and restoring extinction on IS until the test rotation on EW gives complete extinction. (B) Rotate on EW as before. If the grain now departs from extinction more than before depress on NS in the <u>opposite</u> direction and then continue as in (A) until the test rotation on EW gives complete extinction. An OSP lies now $\perp$ to EW. The coordinates of this plane are read on the IS and NS scales and the corresponding great circles plotted on the projection. Rotate 45° on MS and insert a gypsum plate. If the grain is now yellow the great circle on

the projection contains α and β ; if blue it contains β and γ; if a position of extinction is found on testing with EW (an optic axis) then the plane contains α and γ and is so denoted on the projection. If two extinction positions appear (both optic axes) the acute bisectrix is thus determined and, knowing the sign of the mineral, the other two symmetry planes may be immediately found without further Universal stage measurement.

Bring NS and EW back to 0°. Rotate 90° on IS and find a second OSP as before. Select that one which lies less than 45° from the horizontal (measured on the NS scales) as the measurement is thus more accurate. Plot the great circle as before and determine the interference colour with a gypsum plate or the presence of an optic axis. Since α, β, γ lie at the intersection points of the great circles the complete indicatrix is now found constructively. E.g. If the first OSP contains β and γ and the second OSP α and γ then the intersection of the two planes denotes the projection of γ. The third OSP lies 90° from γ and intersects the first two OSP at α and β. The relation of the indicatrix to crystallographic directions depends on the crystal system and only for orthorhombic minerals does the determination of the indicatrix establish unambiguously the crystallographic directions. For monoclinic and triclinic minerals translations, twinnings and cleavages are necessary as well to fix the orientation of a grain.

Measurement of Translation, Twinning and Cleavage Surfaces

Since it is the crystallographic orientations of the grains which is required, the measurement of translation, twinning, and cleav-

age surfaces is of first importance. For isoaxial minerals such as salt and fluorite (L 10) these are the only data obtainable with the Universal stage, and measurement must therefore be carefully made in order that other crystallographic data may be found constructively. It is first necessary to identify the surfaces as (111), (100), etc., as the case may be; then determination of the positions of any two surfaces for a grain serves as a basis for constructive determination of other data. For uniaxials and biaxials the independent determination of optic directions simplifies the matter, and no further data need be computed from the translation surfaces etc., measured in the grain. Also, due to the control by optical measurement, there is no ambiguity concerning the indices of the surface measured.

Select a surface for measurement and, with analyser out and convergent lens in, rotate on IS until the surface lies parallel to one of the cross-hairs. In most cases it is not necessary to bring the translation surface to the centre of the microscope field as no appreciable error arises by failure to do so. Then test on EW or NS (as the case may be) to find that position in which the translation direction shows the finest possible hair-line. In this position it is parallel to the axis of the microscope. Read off the position of the plane on the proper axis, and on the projection plot its <u>pole</u>. Use suitable numbers and symbols so that surfaces can be correlated with the proper optic axes or directions.

For minerals of very high birefringence such as calcite there is a large error in the reading which must be taken

into consideration. With calcite, for example, the common lamellae $(01\bar{1}2)$ and cleavage $(10\bar{1}1)$ must always be set parallel with that cross-hair which is parallel with the vibration plane of the lower nicol (in most microscopes the NS direction.) In this position the readings give the least possible error and for $(01\bar{1}2)$ it is so small that it may be neglected (maximum about 1.) For $(10\bar{1}1)$ there is a maximum error of about 5° when the NS axis is depressed 50°. As it is not an important translation surface, however, its importance is small for petrofabric work.

(c) Oblique Incident Light

For some rocks valuable information may be obtained through examination of a polished section in oblique incident light. For this purpose the surface to be examined is as highly polished as possible and is then covered with an immersion oil close to the index of the rock (e.g. glycerine) to prevent scattering of light from the surface. A cover glass is then placed over this film. An intense convergent light is reflected obliquely on the polished surface and examination is made through a stereoscopic ocular of known ocular distance.

This simple apparatus has the following advantages over the standard Opaque Illuminator - (1) One sees into the grains, not just the polishing and etching marks. (2) Inexpensive and quick method to determine qualitatively orientation, e.g. in calcite lamellae. (3) Indispensable method for study of shape and structure of the intergranular film.

3. Contouring and Rotation of Diagrams

The first representation of a statistical analysis by contouring was made by Schmidt (L 8) and the method has been found very satisfactory to portray maxima and minima and the general distribution of the axes and poles to cleavages in a section. The method is as follows -

Arrange the partial diagrams and data derived from the Universal stage measurements as total diagrams so that they may be contoured. First add up the number of grains and divide by 100 to determine the number forming 1% of the total. Then make a table with two columns, one showing % and the other the number of grains corresponding. The selection of the contour interval (whether 0.5% or 3%) depends entirely on the concentration of the grains and the amount of detail desired.

Lay the diagram to be contoured on a sheet of centimeter squared paper and over both place a blank transparent sheet. Fasten the three pieces together with thumbtacks or paper clips and inscribe a circle on the blank sheet to coincide with that of the underlying diagram. Also mark the 0^{o} point on this upper sheet to correspond with that on the diagram.

The contouring is made with the two celluloid counters shown in Fig. 3. The circular areas are each 1% of the total area of the projection. Counters having 2, 3 and 4% areas are also used but the 1% counter is the most useful. (Radius of 2% counter - 1.43 cm.; 3% - 1.72 cm.; 4% - 2 cm.) They are easily made of cardboard if no better material is available.

Place the central counter on the blank sheet so that

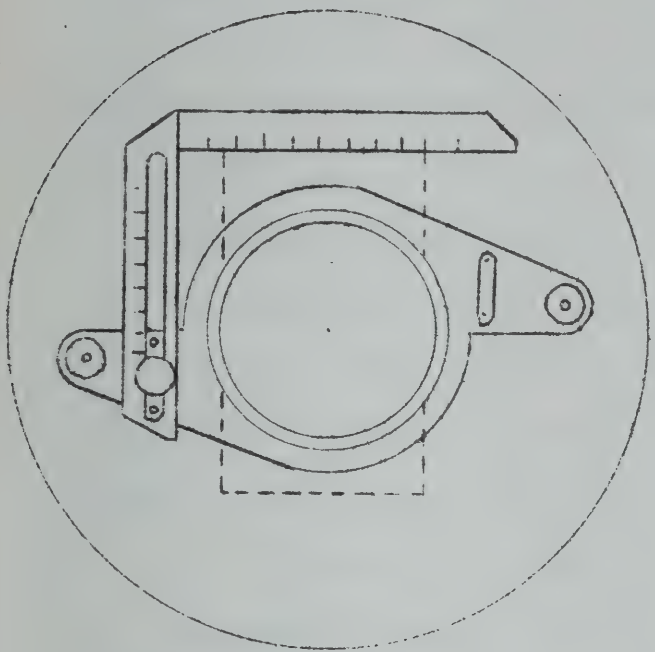


Figure 1

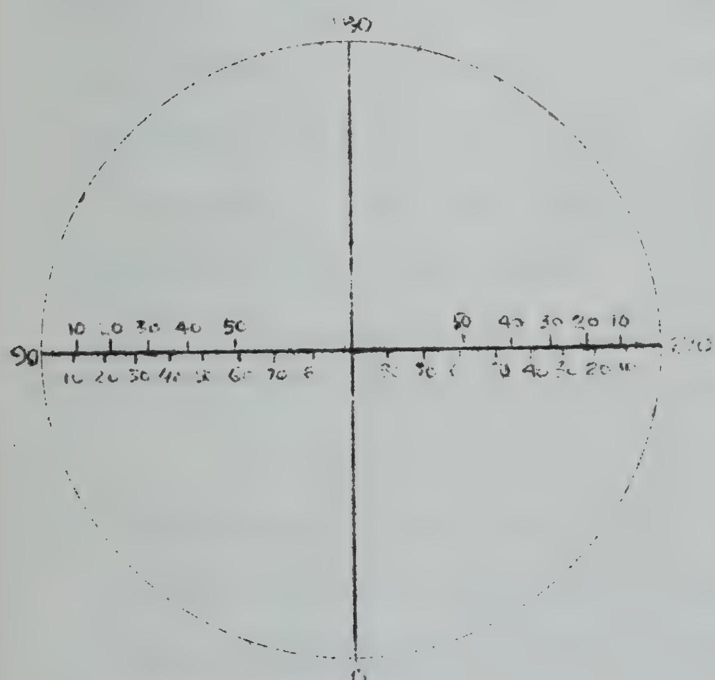


Figure 2

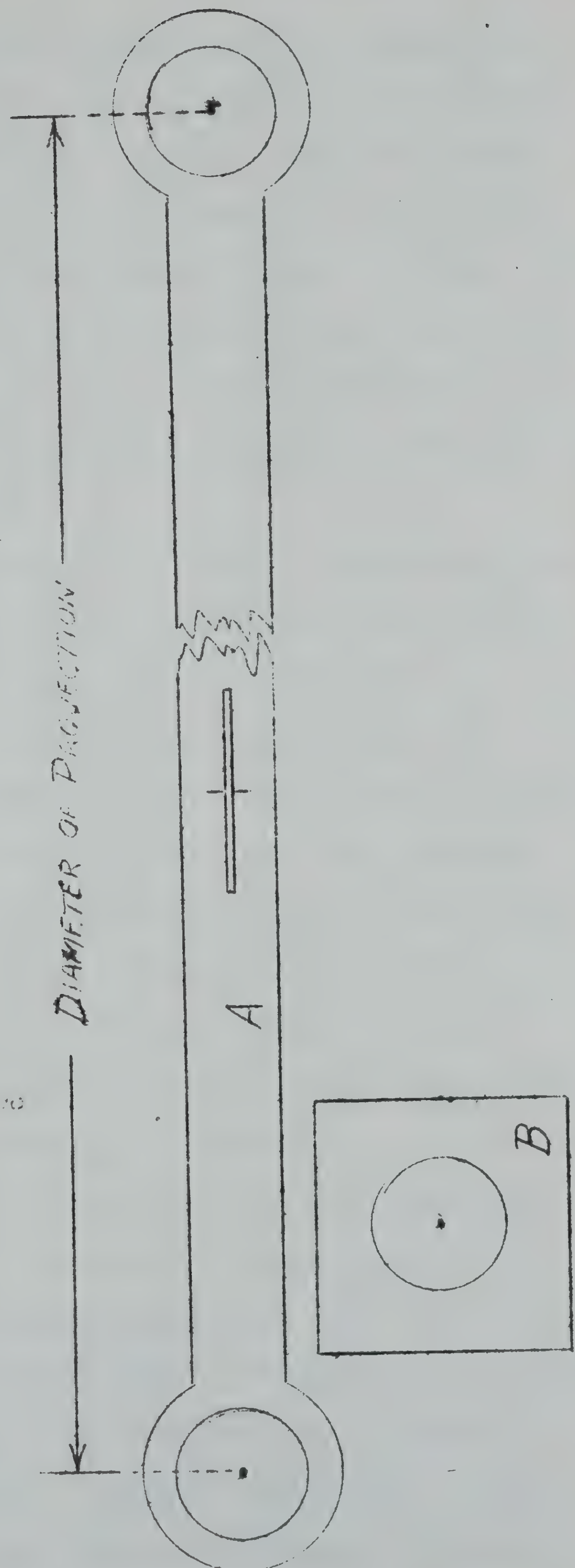


Figure 3

any four centimeter lines of the squared paper are tangent to it. Positions at the margin must not be taken unless the total area of the counter lies within the diagram. Count the number of grains within this area, refer to the table for the nearest corresponding contour and mark this contour number in pencil in the centre of the contour area. Repeat this process by moving the counter around the diagram at one centimeter intervals until finally a contour number appears at every centimeter intersection except those close to the margin.

For the incomplete margin a perimeter counter devised by Schmidegg is used. Place it on the blank sheet so that the middle point in the slit is exactly over the centre of the diagram. Insert a thumbtack at this central point to act as a pivot. Take any initial position and count the number of grains appearing in each of the opposite 1% areas, add them together and with this total find the corresponding contour number from the table. Mark this number on the perimeter in the centre of <u>each</u> of the counter areas. Now rotate the counter to a new position approximately 1 cm. further along the margin and repeat the process until the whole perimeter is covered.

There will still be a number of centimeter intersections close to the margin which could not be numbered by the central counter. Move the perimeter counter so that one of these vacant intersections appears in the centre of one of the 1% areas. Count the number of grains appearing within the two opposite counter areas, add them together, determine the contour number from the table and mark it at the vacant centimeter intersection

selected. The central intersection within the opposite counter area is outside the diagram and is neglected. Repeat for all the remaining marginal intersections. The contour lines are now sketched in as follows - Find the highest contour number and draw its contour midway between it and the next highest contour <u>interval</u>. Interpolation for missing contour numbers is made easy by the squared paper underneath. Each intersection of a contour with the perimeter of the diagram must have a corresponding intersection on the opposite side. Use a straight edge to determine these positions.

The maxima and submaxima are usually inked in as solid black areas; for the outer contoured area various designs and symbols may be used to show up in the best manner the main features of the diagram. All relevant data should be entered at the margin, such as number and type of grains measured, contour interval, the orientation of the thin section to the diagram.

Constructive rotation of a contoured diagram is often desirable for comparison with others differently oriented with respect to the fabric axes a, b, and c. Often it is necessary only to rotate the maxima. The method is the standard one of rotation in the equator direction on the projection and is most conveniently done as follows. Lay the contoured diagram on the equal-area projection (it is assumed to have been drawn on transparent paper) and place over both <u>half</u> of another projection in parallel position. (It must be cut on the 0-180° line.) Lay a blank piece of transparent paper over this and fasten all four pieces together. The half of the diagram now exposed is then

rotated the desired amount and as the other half is covered by the half projection there is no confusion of lines to disturb the eye. Then change the position of the half projection so that the other half of the underlying diagram is exposed and complete the rotation on the upper blank sheet.

C. OPTICAL METHODS FOR OPAQUE MATERIAL

The first fabric analyses of polished sections of opaque minerals by optical methods is that of Korn. (L 11) The work is more laborious than for non-opaque species but is nevertheless of growing importance. The methods heretofore have been complicated and impractical for statistical work, but in a recent paper (L 11) Korn has presented simplified solutions for the determination of the spatial position of such opaque minerals. Two of these constructive solutions are described here; others have been worked out but are not all as yet published.

The grains to be measured must show evidence of twinning, translation or cleavage and in many cases it may be necessary to resort to etching solutions in order to bring out these features. Further, the indices of the surface measured must be known at the start, a condition which e.g. for galena and most common opaque minerals presents no difficulty.

Determination of Orientation from Measurement of (100)

Three traces of (100) must appear on the surface of the polished grain. The poles to these three traces are represented by the lines C_1, C_2 and C_3 in Fig. 4 . The poles to the cube

surfaces lie therefore on these lines.

Turn the projection paper so that one line (in this case C_1)lies exactly EW. Then by trial find that great circle which subtends an angle of 90° on C_2 and C_3. These two intersections represent two of the poles to cube surfaces. The third lies on C_1 90° from the great circle. As the diagram shows, the solution has one degree of freedom and the position of a grain is not accurately fixed unless other surfaces (such as octahedral) are also measured.

Determination of Orientation from Measurement of (III)

The orientation of grains showing octahedral cleavages may also be determined constructively. The method is more complicated than that for cubic cleavages but is nevertheless practical. Allowance must be made, as with measurement of cubic cleavages, for possible degrees of freedom.

Use of Universal Stage

The Universal stage can be used to advantage on those grains in which cleavage pieces are broken out of the surface by grinding. Such surfaces can be directly measured and the constructive solution is then unnecessary. In practice a combination of the two methods is advantageous in order to measure the maximum number of grains in a section. There is no standard equipment at present available for mounting a section on the Universal stage. The hemispheres must be removed and the section fastened on the inner stage by some means so that the polished surface is perpendicular to the axis of the microscope.

D. X-RAY METHODS

The possibilities of X-ray analysis were first described in 1930 by Sander and Sachs (L 12). Since then Sander has been active in this field and has much unpublished material on hand.

The method is simple; the interpretation of the photographs however requires care. A molybdenum target is desirable as the resulting radiation is hard and more penetrating than that from other targets in common use. The radiation should also be approximately monochromatic since the combination of polychromatic radiation on a section containing many minerals and many more reflection surfaces makes the photographs unnecessarily difficult to interpret. The effect of the radiation is recorded on a plate or cut film suitable for X-ray work and shows as a series of concentric rings.

The material to be examined is prepared (1) as a thin section or (2) with a flat ground surface. By 'thin' section is not meant, as in petrographic work, a 'transparent' section but only that it is thin enough (e.g. .20mm) that the radiation penetrates it without unduly long exposure being necessary. The best thickness depends on the material and can only be decided by trial and experience. The section is set up in a suitable holder and its fabric and geographic coordinates carefully noted with respect to the radiation and the film.

The second method of preparation requires only a flat surface and the radiation is reflected back to the film which in this case is placed between the specimen and target. A hole in the film allows the primary radiation to pass through to the specimen and is made large enough so that no blackening of the film occurs.

The area encountered by the rays must be homogeneous in texture and composition; otherwise the photograph is useless.

For relatively coarse-grained material a clockwork or other automatic device is used to move the specimen in parallel position back and forth $\perp$ to the radiation. In this way a sufficiently large number of grains are brought into contact with the rays to ensure a successful photograph. For fine-grained material such as slate this is of course unnecessary.

The photographs have two purposes, either (1) to show only symmetry or (2) to allow interpretation of the rings as definite reflection surfaces. For (1) a photograph need have no particular detail and relatively short exposure may suffice. For (2) as much detail as possible is required and to this end a small opening is used with consequent great increase in exposure time. Such calculations have been made successfully for monomineralic rocks such as quartzite (L 12) but for a complex like slate in which not even all the minerals are accurately determined a calculation is attended with more difficulty.

X-ray analysis has the following advantages - (1) The exact orientation of the grains can be found. With optical analysis this is possible only with orthorhombic minerals. With all other systems the grains have a freedom of movement which by optic means alone can not be controlled. (2) When only symmetry is desired an X-ray photograph saves much labour and time. (3) Material too fine-grained for optical analysis can be photographed and the symmetry established.

It has the following limitations - (1) In making a calculation of reflection surfaces an optical analysis is at the same time necessary to provide a starting-point. (2) An

X-ray photograph shows only the orientation of the crystal lattices; the dimensional orientation and shape of the intergranular film must be determined optically. (3) Submaxima found in optical analysis do not usually appear in a photograph and are often very important. The photograph tends to give the symmetry of the grain, not of the fabric as a whole.

In conclusion it may be said that optical methods are still the more useful in all cases in which the material can be measured by optical means. X-ray analysis should be accompanied as far as possible by optical measurement in all cases where exact data on the orientation are required. For quick determinations of symmetry on 'c' sections this is unnecessary. The usefulness of X-ray analysis is not yet fully known and in time the methods will certainly be improved.

E. USEFUL CHEMICAL TESTS

Hirschwald's Colour Method

A rock surface which is to be examined is polished and immersed for 48 hours in an alcoholic nigrosin solution. The arrangement of the intergranular film and of all fractures is then very clearly seen with the naked eye due to the action of the chemical. If examined in oblique light by the previously described method more detail may be obtained. The method is especially valuable for rocks such as calcite and dolomite marbles which do not always show visible planes or directions in a hand specimen.

Distinction of Calcite and Dolomite

A quick and practical method of distinguishing between calcite and dolomite in a hand specimen is made as follows - The surface intended for examination is finely ground (not polished) and wetted with water. (As all grease and oil must be removed it is advisable to re-grind the surface directly before making the test.) Then pour $FeCl_3$ solution over the surface and wash again gently and thoroughly with water. Apply $(NH_4)_2S$ solution which has been thoroughly saturated with H_2S (such a solution has a yellow colour) and wash again with water. With this treatment calcite turns black and dolomite is unchanged.

These two tests are successfully used in Innsbruck as an aid in petrofabric work. Others may be used where the need arises.

DEFORMATION FABRICS

Deformation fabrics consist of two groups - those in which the continuity of the structure is retained despite the movements, and those in which it is not retained. The latter case is represented by a process such as brecciation and has little regional significance. The movements involved in the former type are of great importance tectonically and are known as partial-movements, Sander's definition is - "As partial-movement we name each movement of any element in a rock, as a result of which, after the deformation, and for the time under consideration, the rock retains its continuity." Rocks in which these partial-movements are integrable to some tectonic pattern or symmetry shown by grain orientation are known as tectonites, a useful genetic term which covers many classes of rocks described ordinarly as foliated, slaty, banded, or even massive.

Most tectonites are characterized by megascopic surfaces and directions. A direction is, as a rule, still visible. In few rocks is the fabric megascopically isotropic. For convenience therefore three reference axes are set up as follows -

'b' denotes the direction seen in the rock. It may be shown as a direction in a foliation surface, as the intersection line of two or more foliation surfaces, or as the axis of a fold. It may be called "tectonic axis". If accessory directions are present they may be denoted as b', b" etc.

'a' lies $\perp$ 'b' in any surface $\parallel$ to which shearing movements are indicated. Its exact position is usually determined

only by a statistical investigation, commonly two or more 'a' directions are found. Its significance therefore, as the direction of transportation of material will be left till later.

'c' lies by definition $\perp$ to any surface formed by 'a' and 'b'.

Surfaces in a rock are described with relation to these three axes in crystallographic terms. Thus, if the axes are set up so that 'b' runs EW, 'a' NS and 'c' vertical, it is seen that the foliation surfaces which have 'b' as a common axis are at the same time 'h0l'-surfaces. Similarly, 0kl and hkl surfaces are known. Not only foliation surfaces, but all megascopic or megascopic or microscopic joints and fractures, may be described in these terms. This method renders it easy to mentally picture the three dimensions occupied by the fabric and saves much needless description.

Following up the crystallographic method we speak of the <u>symmetry</u> of a fabric. It is a statistical conception, shown by the grain orientation in its relation to the megascopic fabric. Every fabric shows upon statistical analysis the symmetry of the vector fields which acted on it during deformation. The following four types of symmetry are found -

(1) <u>Spheroidal</u>, or the symmetry of an oblate ellipsoid in which two axes are equal and greater than the third. Rocks containing a single set of parallel surfaces having no diagnostic line in the surfaces, (and, therefore, no visible 'b' axis,) and sediments deposited from a non-flowing medium illustrate this symmetry. (It is possible also that fraction-

al crystallization of magma under conditions of no flow and no stress illustrate spheroidal symmetry.)

(2) Rhombic - three unequal right-angled axes - symmetry of a tri-axial ellipsoid. Rocks containing two sets of equally well-developed parallel surfaces which intersect in the 'b' axis.

(3) Monoclinic - As used here, having one symmetry plane. Rocks having one h0l-surface with a diagnostic line in the surface ('b' axis), or having several unequally developed h0l-surfaces with a common intersection line parallel to the diagnostic line 'b'. This is the common symmetry of tectonites.

(4) Triclinic - Having no symmetry plane. Commonly shown in tectonites as intersecting h0l, 0kl or hkl-surfaces.

Tectonites are further divided into two classes, depending on the type of diagram which their grain orientation reveals. If the orientation shows on the diagram as one clear-cut maximum or two or more clearly separated maxima we speak of an S-tectonite. If, on the other hand, it shows as a girdle, complete or incomplete, and with or without important submaxima, we speak of a B-tectonite. All stages of transition are possible between the S- and the B-types, and from them to complete lack of any orientation. The B-tectonite is much the commoner and will be discussed more fully later.

Tectonite Orientation Rules

Since the manner in which minerals behave during formation of a tectonite is the basis of petrotectonic analysis, the

known data are summarized here for convenience.

<u>Quartz</u> - The orientation of quartz, the commonest mineral in the upper crust of the earth, is still not completely understood.

Its lattice orientations fall under two heads as follows - Orientations connected with translation parallel or sub-parallel to prism planes, and orientations connected with translation or twinning on rhombohedral planes. We may call them provisionally the <u>prism rules</u> and the <u>rhombohedral rules</u>.

1. <u>Prism Rules</u> - Orientation of quartz after a prism rule is extremely common. This is illustrated particularly well in quartz having undulose extinction. The vertical axes of such grains are sub-parallel to the directions shown by the usually parallel "strain" shadows. In cases there are parallel ruptures associated with these shadows which Sander finds lie 6-12° from the vertical axes of the grains. (See L 2 , Abb. 67) In recrystallized quartz (in which there is no remaining evidence of undulose extinction and corresponding ruptures) the exact prism rule cannot be determined. The vertical axes lie approximately parallel to any prominent shear surface and normal to the fabric axis 'b' (Fig. 23 and others.) Optic analysis does not determine which prism, or near-prism, plane is favoured as a translation surface. This is possible only from X-ray study.
2. <u>Rhombohedral Rules</u> - One rhombohedral rule is already established and the presence of a second one is suspected. The first is translation parallel to Boehm's lamellae. In 1883 a

German geologist, Boehm, noted fine striations on many quartz grains which he examined. These are now known to be the traces of rhombohedral lamellae whose poles make angles varying from 20^{0} to 23^{0} with the vertical axes. (Determination by Sander.) This surface may be the rhombohedron $\omega(01\bar{1}3)$, since the angles check fairly accurately. Translation after this rhombohedral rule may occur without visible evidence, necessarily, of the lamellae (Cf. p.66 and accompanying figures.)

The second, suspected, rhombohedral rule is a twin rule. The evidence given on p.58 indicates statistically the orientation of $r(10\bar{1}1)$, as a twinning plane, parallel to a shear surface.

There is only one common rule shown by a true dimensional orientation of quartz - i.e., orientation of rod-like grains with their longest dimensional axes parallel to the axis of rotation 'b'. The pseudo-dimensional orientation described on p.79 is, as the name implies, not a true dimensional rule.

Calcite - The lattice orientations for calcite form two rules (1) - The e-rule in which $e(01\bar{1}2)$ is oriented in a shear surface; (2) - The r-rule in which $r(10\bar{1}1)$ is oriented in a shear surface; The e-rule is much the commoner and the $(01\bar{1}2)$ lamellae lie with their short diagonals parallel to the direction of translation 'a'. Further, the acute angle between the optic axis and the short diagonal is in most cases in the direction of 'a'. The same may hold for the poorly developed r-rule but there are too few data at present to warrant any statement. No cases of true dimensional

orientation are known for calcite, but the same principle of orientation with respect to the axis of rotation 'b' should hold as for quartz.

<u>Mica</u> - Lattice orientation of mica consists almost entirely of a basal <u>pinacoid rule</u>, in which the base, (001), is oriented parallel to a shear surface. In muscovite, the 'a' crystallographic axis is parallel to the 'a' fabric axis. A second lattice orientation of mica is known in which translation occurs on a crystallographic plane steeply inclined to (001). As with quartz, there is only one common rule shown by a dimensional orientation-i.e., orientation of basal flakes parallel to shear or plaiting surfaces, or, in absence of these, parallel to the axis of rotation 'b'.

<u>Hornblende</u> - The orientation of hornblende follows two <u>pinacoidal</u> rules. In both, (100) is parallel to a shear surface; in the one with the vertical axis parallel to the axis of rotation 'b', in the other with the vertical axis parallel to 'a' of the fabric. To what extent the former represents a dimensional orientation is not yet established.

<u>Feldspar</u> - The orientation of feldspar (only highly albitic plagioclase is included here) follows two <u>pinacoidal</u> rules, similar in type to those for hornblende. In both, (010) is parallel to a shear surface. The one rule shows the vertical axis parallel to the rotation axis 'b' of the fabric; the other shows it parallel to 'a'. As with hornblende, the extent to which the former rule represents a dimensional orientation is not yet established.

Epidote - Preliminary work on epidote shows a rule in which the long crystal axis 'b' lies parallel to the 'a' fabric axis. Probably a pinacoid or prism is oriented in the shear surfaces, but no determination has yet been made. (Unpublished data of the writer)

Gypsum - The orientation of gypsum follows at least one pinacoidal rule, in which (010) is oriented in shear surfaces with the vertical axis sub-parallel to the rotation axis 'b' of the fabric. (L 13)

Fluorite - Lattice orientation of fluorite consists of an octahedral rule in which (111) is oriented in shear surfaces either by translation or twinning. (L 10)

Tourmaline - See L 14. Reference not available at present to the writer.

Scapolite - The vertical axis (c') lies in the foliation surfaces (L 15). A preferred glide plane or glide line has not yet been established. Experiments dealing with glide planes and directions in single crystals are also lacking.

Tectonite Analysis

Introductory Example - From the definition of a tectonite as a rock which has undergone partial-movement, it is seen that a direct connection must exist between the orientation rules just described and the mass movement of material which, we have good reason to believe, took place in deformed parts of the earth's crust. An

excellent example illustrating this relationship is described by Schmidt (L 8) in the first Universal stage analysis to be made of a rock fabric. He selected material from an area of paragneiss in the Eastern Alps in which the field structure is relatively simple and uniform. The direction of movement is assumed, as elsewhere in the Alps, to be NS, normal to the fold axes. The minerals, due to their pronounced unequal dimensions, indicate a conspicuous EW direction, the 'b', or tectonic, axis of the fabric. The foliation surfaces are well developed. Quartz and oligoclase are the most abundant minerals, with biotite, some muscovite, and rarely microcline. Quartz was measured in eight sections over an EW length of 20 km. and, as the orientations in each are similar the results are shown schematically in Fig. 6. 'a' represents NS 'b' represents EW geographically. A girdle of axes parallel to 'ac' and $\perp$ to the plane of schistosity 'ab' is conspicuous. A maximum appears in 'a' and a smaller one in 'c'. We will consider at this point however only the maximum in 'a'. The axes lie in a zone $\perp$ 'b' and parallel to the direction of movement, with a strong concentration in the foliation surface parallel to the assumed NS direction of movement. This relation between the orientation of the quartz axes, the surface of foliation and assumed direction of movement in the surface is not accidental. We are dealing with a lattice orientation in which the quartz axes may be thought of as radiating statistically like <u>bristles</u> from the hub of a rotary brush, with some of the bristles particularly large and strong. If our assumption of the NS direction of movement in the foliation surface is correct (and in the Alps all evidence

points in that direction) then the maximum in 'a' (prism rule) indicates that the quartz prism faces act as gliding planes during the deformation, with moreover, a preferred direction, a glide line, in that plane parallel to the vertical axis. This set-up of a girdle of axes parallel to 'ac' and normal to 'b' is characteristic of B-tectonites and forms the bulk of all cases investigated. The maximum in 'a' is commonly found, as well as several others which will be discussed on a later page. Study of relatively simple well-defined cases such as this one serves therefore as a basis for analysis of less obvious field structures in which much dependence must be placed on the position of the girdles and the maxima they contain. We turn now to hypotheses of origin of tectonites such as the one described.

The Strain Ellipsoid - The mechanical basis for lattice orientation in tectonite is furnished by the strain ellipsoid. Over a rock unit which has been homogeneously strained, straight lines remain straight, planes remain planes etc.; in consequence, there can be no folding or bending of material in the unit under consideration. Folds imply inhomogeneous strain, to which the strain ellipsoid cannot be applied. Each part of a fold has its axes of strain differently oriented from those of a neighbouring part. Infinitely small parts of a folded structure may be considered as being strained homogeneously but the strain in the whole unit can not be considered homogeneous unless the above condition is fulfilled.

We use the following axes of strain - A is the long axis, B the intermediate axis, and C the short axis. The two

planes of no distortion intersect in B; the maximum slip or displacement takes place parallel to these planes and in a direction parallel to the AC plane. We are speaking here of two dimensional strain, or <u>plane deformation.</u> "A solid body suffers a plane deformation, or is deformed in two dimensions, if its deformation fulfills the condition that all displacement results along a group of parallel planes (AC) and that displacement for all points on lines $\perp$ to each of these planes are similar and parallel." (L 2) Any one of these planes may be called a deformation plane. Only with a plane deformation do we have <u>circular</u> sections, representing sections in which slip occurs with <u>no distortion</u> of the material affected. These two sets of circular sections may have initially any position inclined to A or C then, with increasing strain, approach a limiting position in the AB plane. In the AB plane itself no movement can occur.

The direction in which the chief stress is applied localizes the axes of strain insofar that the plane AC (plane of deformation) is sub-parallel to it. B is by definition $\perp$ AC and the strain produced may be one of two types - depending on the position of the chief stress with respect to the deformation plane. <u>Non-rotational strain</u> is defined as a plane deformation in which the axes of the strain ellipsoid are not rotated with respect to fixed co-ordinates and the two sets of circular sections rotate, or "flatten", <u>equally</u>. This type of strain is produced in experiments if the chief stress acts parallel to C. The circular sections flatten out the same amount in an equal time.

Rotational strain is defined as a plane deformation in which the axes of the strain ellipsoid are rotated with respect to fixed co-ordinates and in which the circular sections rotate unequally. Fig. 7, in which XY are the reference axes, indicates this condition; A and C rotate to new positions A' and C' and the circular sections rotate from S_{ABC} and S'_{ABC} through the shaded areas to take up new positions $S_{A'BC'}$ and $S'_{A'BC'}$ as shown. The feature accompanying rotation of the axes about B is that the circular sections rotate different amounts and at different speeds; the one rotating least forming the smaller angle with the assumed chief stress direction. The extreme case of rotational strain is illustrated by so-called "scission" in which only one circular section shows rotation. The sliding of cards over one another illustrates this extreme case.

From the standpoint of rock deformation these cases have different values. Becker's statement of the probable point of application of a chief stress expresses (geometrically) the situation admirably (L 16). In summary he says: "The direction of a force with reference to a resisting plane may be regarded as fortuitous. If variations of plus or minus half a degree are tolerated, the chance that the force is acting 90° to the plane is 20,626, which is the number of square degrees on a hemisphere of unit radius. On a zone 45° to the plane the chance rises 255 times. The average value of all possible inclinations is an angle of one radian ($57^{\circ}18'$) to the normal. Thus pressures at less than 45° to the plane are more probable than those at higher angles, and normal pressure is least probable of all. Unmodified

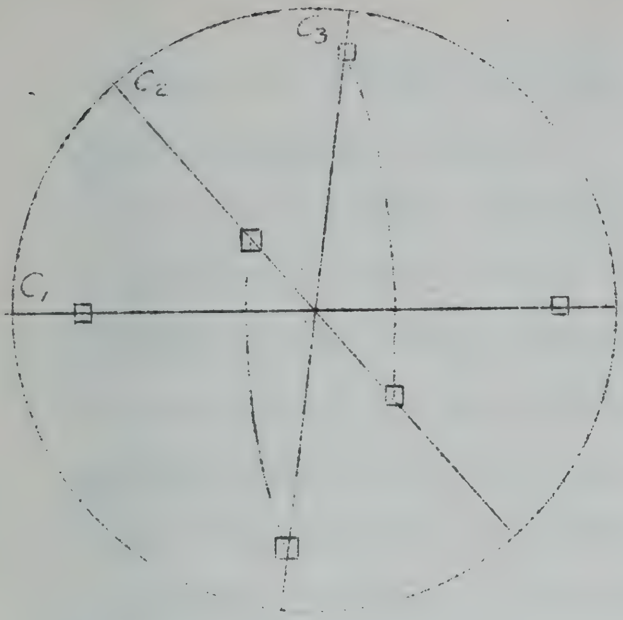


Figure 4 p. 26

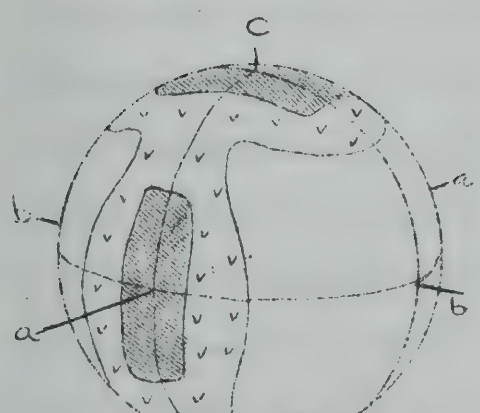


Figure 6
p. 39

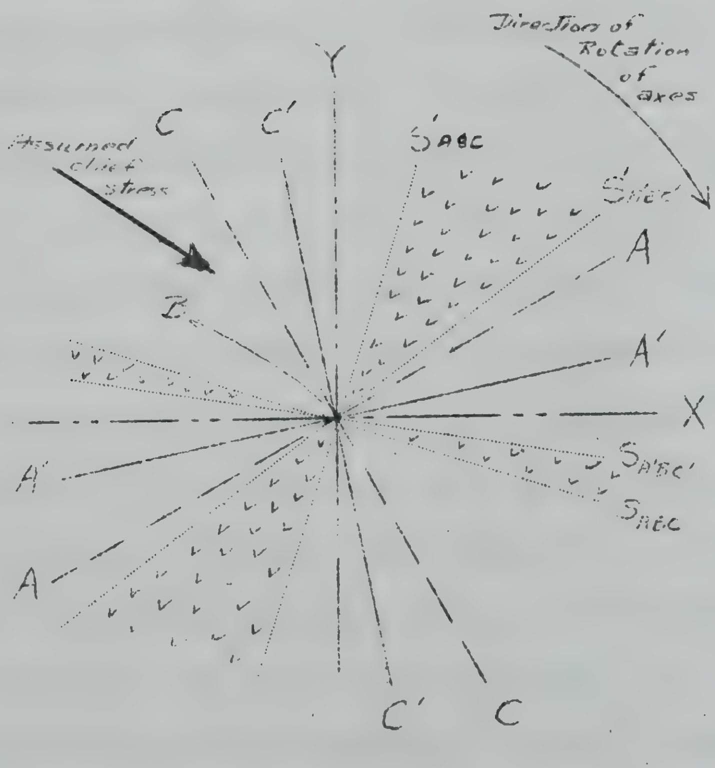


Figure 7 p. 42

scission is a limiting case, but 360 times as probable as pure (non-rotational) strain."

The odds in nature against non-rotational strain are probably not quite as high as this purely geometrical survey would indicate, since material may yield in such a way that approximations to non-rotational conditions occur. However, the average position of the chief stress is probably inclined less than 45° with AB of the strain ellipsoid. The general case of rotational strain as shown in Fig. 7 has therefore most interest for us in a consideration of tectonites.

Development of Quartz Orientation - There is as yet no general theory of the process of grain orientation in rock fabrics. We have only hypotheses with which to attempt an explanation of the known data. In the case of the gneiss investigated by Schmidt the grain orientation in a girdle is now known to be typical of tectonites and a working hypothesis is essential. The gneiss has undergone most certainly many deformations, of which the last one is represented by the girdle of Fig. 6. For simplicity, however, let us assume that the rock has suffered only one deformation and that it was composed initially of equidimensional quartz grains. The deformation plane AC lies NS geographically, and is approximately vertical. It contains the 'a' fabric axis and is sub-parallel to the chief stress direction. The exact positions of A (direction of elongation) and C (direction of shortening) of the structure might be given by the attitude of flexure folds within the gneiss, if such were present; uncertainty regarding A and C, however, is more common than not and does not vitiate the development of the hypothesis in any way. B is normal to the AC deformation plane.

The relation therefore of the strain axes ABC and fabric axes 'abc' is as follows - A is not parallel to 'a'
B is ~~not~~ parallel to 'b'
C is not parallel to 'c' (See Fig. 8)

This case holds not only for this example but for the relations of strain and fabric axes in general.

Movements in the fabric take place either in (intragranular) or between (intergranular) the grains. Lattice orientation of minerals indicates intragranular movement; dimensional orientation, in general, indicates intergranular movement. The ratio between the amount of intra- and inter-granular movement depends on the orientation of the grains with respect to the shear directions imposed on the rock. Until the grains reach a favourable position for gliding it is assumed that intergranular movement predominates. This position is determined by the orientation of the shear directions. From Fig. 7 we see that for rotational strain these two directions sweep through the fabric during the progress of the deformation, but at varying rates. That is, from the standpoint of the final stage of the deformation, that direction of shear which has passed through the smallest 'wedge' of material will be preferred as a direction in which orientation of the elements occurs. The movement approximates more closely to a plane in this direction than in the other and this is therefore the more effective direction of shear. The quartz grains tend to rotate therefore until their vertical axes lie at least sub-parallel to the deformation plane (AC) and to the favoured direction of shear (in the S_{ABC} $S_{A'BC'}$ wedge of Fig. 7.) In this direction gliding sub-parallel to prismatic

lattice planes occurs, of which we have evidence from the maximum in 'a' of Fig. 6. Since the amount of gliding along these planes is limited (without assuming disturbance of the lattice) it is obvious that for many grains the maximum translation will be reached before the deformation is finished; intergranular resistance may become, as a result, relatively smaller than the intragranular resistance and the grain will again suffer rotation. This rotation we name <u>external</u> in contrast to the <u>internal</u> rotation illustrated by the strain ellipsoid. The external rotation at this stage of the hypothesis is localized, however, sub-parallel to the deformation plane AC and there will be little tendency for the axes of grains originally oriented in 'a' to deviate very far from the fabric plane 'ac' (= deformation plane AC). Many of these grains, however, will be rotated out of this position in 'a' to form the girdle which characterizes a B-tectonite. Without this external rotation we would have an S-tectonite; i.e., maxima only. The predominance in general of B-tectonites, however, indicates the important role that external rotation plays in deformation. Its effect, by forming a girdle, indicates clearly the position of the deformation plane AC and of the tectonic axis 'b' (= B).

<u>Significance of 'b' axes</u> - The 'b' axis of the gneiss considered in the foregoing example is defined largely by parallelism of the longest dimensional axes of the predominant quartz. If this represents actual elongation of grains then it would seem that the assumption of B (strain) equals 'b' (fabric) has no basis, and that A (long axis of strain) should equal 'b' (fabric). The

The evidence from fold axes and the girdle however indicates that A and 'b' are not parallel, but normal to each other and we must seek another explanation for the elongation parallel to 'b'. The case is typical of tectonites in general and the hypotheses outlined below have therefore general application.

A plane deformation allows elongation parallel to B as well as to A, since it is a property of an ellipsoid that, as its circular sections approach parallelism with the AB plane, B must also approach A in length. Strain in rocks beyond the elastic limit involves "flattening" of the circular sections, so that B must be considered at all times as at least a minor axis of elongation. The hypothesis already set up to explain girdles normal to 'b' emphasizes the importance of external rotation (intergranular movement, or rotation of the whole rock mass). This means that a grain, although elongated initially parallel to A, does not necessarily remain in this position. It is rotated further in the girdle (sub-parallel to AC) and the direction in which it was originally elongated reaches sooner or later a position parallel to the axis of shortening C. The original elongation is thus effectively obliterated and appears in a new direction. The mass effect of this external rotation is to prevent elongation parallel to A from becoming effective. On the other hand, since B is the axis of external rotation and at the same time an axis of elongation it represents a favoured direction of elongation under the conditions postulated. Any assumed grain, rotating sub-parallel to AC, possesses one direction which is exposed constantly to elongation parallel to B

throughout the entire deformation; on the other hand, it possesses no one direction which is exposed to elongation parallel to A for more than a small fraction of the total time of deformation. Thus the <u>effective</u> elongation develops parallel to the minor axis of elongation B, rather than parallel to A. (See further discussion on p. 69)

In support of this idea of <u>effective</u> elongation is a further important property of the strain ellipsoid. If a sphere of diameter 1 is deformed to an ellipsoid without change of volume, the axial ratio of A, B, and C must be such that the condition (no change in volume) is satisfied. We have already indicated, however, that, as the circular sections approach parallelism with AB, B must approach A - i.e., $B > 1$. To fulfill the volume relation, therefore, $B > \frac{A + C}{2}$ by some given amount. In terms of external rotation and elongation parallel to B in tectonites, the net effect of the alternate elongations and shortenings imposed on grains in the AC deformation plane is such that <u>actual</u> elongation can only take place parallel to B. Constant volume is assumed throughout. With respect to the external rotation <u>alone</u>, the deformation is of the type that could be represented by a prolate ellipsoid whose long axis is B. The presence of shear planes demands a tri-axial ellipsoid, however, since only <u>conical</u> fracture surfaces can be formed from a prolate ellipsoid.

In addition to actual elongation parallel to B, <u>apparent</u> elongation may be caused as follows - Since 'b' is the axis of rotation, it is the locus of the intersection line of shear surfaces. The combined effect of external rotation and shearing

normal to a common axis means that fresh material is constantly passing through the favoured shear directions. This may result in rupture of grains into rod-like elements arranged parallel to 'b' which gives an <u>apparent</u> elongation normal to the deformation plane AC. It may also emphasize actual elongation in B. Whatever the merits of these hypotheses of actual and apparent elongation parallel to B, there still remains a body of facts concerning shear surfaces, 'b' axes, grain orientation etc., which do not fit in with pre-existing hypotheses and require, therefore, fresh interpretation. The facts and interpretation of this introductory example of a tectonite will be amplified in the following pages by others so that the reader will have a broader basis for his own conclusions.

Relation of Recrystallization to Deformation

The partial-movements which form tectonites are of two kinds - direct and indirect. <u>Direct partial-movement</u> involves actual mechanical movement, external and internal, of the fabric elements under consideration. <u>Indirect partial-movement</u> includes all molecular mobilization of elements initiated by the direct partial-movements. It includes such processes as diffusion, solution and recrystallization in so far as they are dependent upon the mechanical movements. We conceive, therefore of this molecular action as healing ruptures, filling minute cavities etc. which result from the direct partial-movements. Since this recrystallization occurs simultaneously with the deformation we speak of it as para-tectonic crystallization, or

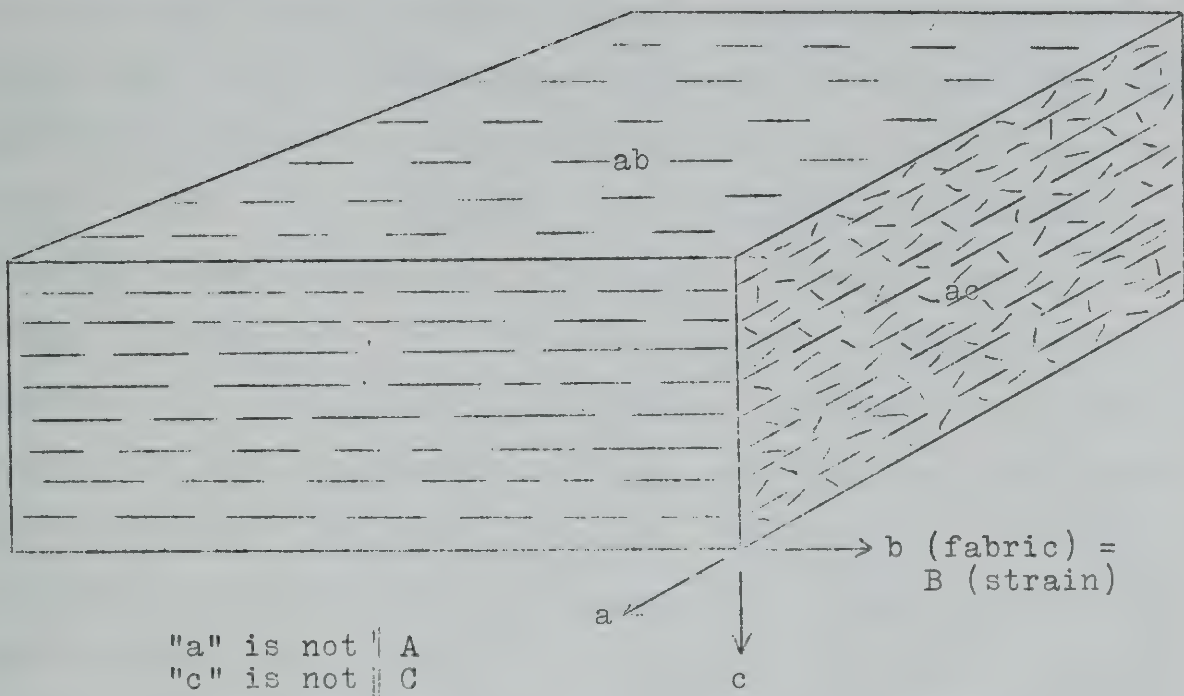
conversely of the deformation as a <u>para-crystallization deformation</u>. In a similar sense we describe a recrystallization which is active after the deformation is over as a <u>post-tectonic crystallization</u> and of a recrystallization which does not accompany the deformation to its final stage as a <u>pre-tectonic crystallization</u>. Expressed in terms of the deformation the two terms are, respectively, <u>pre-crystallization deformation</u> and <u>post-crystallization deformation.</u>

<u>Evidence of Movement</u> - Direct evidence of these time-relations of deformation and recrystallization is to be found microscopically in certain fold and relict structures. The evidence from folds is shown particularly well by mica. A fold formed of mica laths which show no bending or other distortion illustrates post-tectonic crystallization; a fold in which the laths are bent and distorted illustrates pre-tectonic crystallization. If both types occur together we have para-tectonic crystallization.

The evidence from relict structures is still more convincing. The well-known type which is preserved within porphyroblasts is known as an <u>'si' fabric</u> ('s' from schistosity surface and 'i' from internal) in contrast to the <u>'se' fabric</u> ('s from schistosity surface and 'e' from external) in which the porphyroblast has grown. There are many uses for these relict, 'si' fabrics, not the least of which is the evidence they furnish regarding post-, para-, and pre- tectonic crystallization. Fig. 9 illustrates post-tectonic crystallization. A porphyroblast has grown in a foliated tectonite and the

residual 'si' is continuous with 'se'. No movement has occurred since growth of the porphyroblast. Fig. 10 illustrates pre-tectonic crystallization. The porphyroblast has grown during a period of quiet, as in Fig. 9; growth has then ceased and deformation again occurred as shown by the non-parallel positions of 'si' and 'se'. In contrast to these two types Fig. 11 illustrates by steps the ideal development of para-tectonic crystallization - contemporaneous growth of the porphyroblast and deformation, shown by rotation. S-curves of various types are developed by 'si' and form the criterion for this type of crystallization. (a) is an initial stage during which the nucleus of the porphyroblast has grown and in which 'si' is parallel to 'se'. (b) is a second stage during which the porphyroblast has grown further by assimilating 'se'. The new growth shows 'si' parallel to 'se', but 'si' of the nucleus has rotated with respect to 's'. (c) represents a further stage. The final result is shown as an 'si' of S-curves, continuous with 'se' only at the boundaries of the host.

The distinction of para-, pre-, and post-tectonic crystallization is of importance in describing the elements of a fabric. A recrystallization may, for example, be pre-tectonic with reference to one mineral and post-tectonic with reference to another, with a different orientation involved in the two cases. A post-tectonic crystallization in which some pre-existing structure or texture (e.g. a fold) is preserved, is known as an Abbildungskristallisation. Para-tectonic crystallization is shown in a deformation, as previously noted, by <u>indirect</u> partial movements and is a highly important type although



"a" is not ‖ A
"c" is not ‖ C

"ab"=schistosity plane. Contains diagnostic line ‖ to"b"
"ac"-fabric plane = AC - deformation plane

Figure 8 p. 44

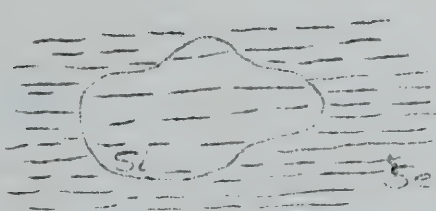


Figure 9 p. 49

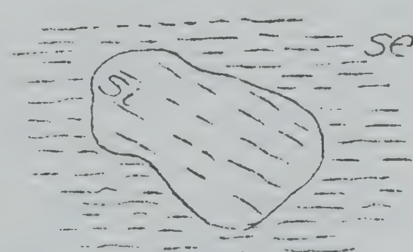


Figure 10
p. 50

(a) (b) (c)

Figure 11. p. 50

direct evidence of it, is not everywhere easy to find. The mechanics of these indirect partial-movements may depend in large part on the phenomenon of dilatancy, well known for loose granular aggregates, and first given geologic significance by Mead (L 1[illegible]). The principle is well illustrated by a bather walking along the wet sand of a beach. With each step the water is drawn away from the neighbourhood of the foot and immediately is returned when the pressure is released. In explanation, the sand is normally in close packing, i.e., the volume of the interstitial space, or voids, is a minimum. Pressure by the foot disturbs this arrangement by increasing the voids and therefore the volume of the material affected by the pressure. As there is initially just enough water to occupy these voids, there is now a decrease in fluid pressure and water is drawn in from the surrounding, unstressed, area to restore equilibrium. Thus the "dry" area around the foot is explained.

In a non-reversible deformation (failure by flowage) Mead suggests that the solid and fluid phases of a granular aggregate may be thought of, in deformed rocks, as representing competent and less competent material, with a certain amount of a true liquid phase. Direct partial-movements, as described previously, open minute ruptures in and between grains and thus set up indirect partial-movements, causing shifting and reorganization of the more mobile (less competent) material so as to tend to restore the equilibrium.

The perfection of this "follow-up" of para-tectonic crystallization is governed partially by the velocity rule of partial-movement - which states that the velocity of relative

movements between the elements of a fabric depends on their size. Fig. 12 illustrates the rule. In a horizon of constant thickness an absolute movement of 'x' in a time 't' is assumed. In (a) the elements are assumed to be of such a size that movement occurs along '6' parallel surfaces; in 'b' the elements are twice as large and there are only 3 surfaces to take up the whole of the absolute movement 'x'. The velocity of relative movement for each of the small elements (represented by the distances between adjacent surfaces) is $v=x/6t$; for the larger elements it is $v=x/3t$. Thus the direct dependence of size of element on velocity of partial movements is brought out.

If this velocity (decided by size of element) exceeds a certain limit then indirect partial movement cannot follow directly and para-tectonic crystallization does not occur. Only direct partial movement is effective, ruptures remain unhealed and a cataclastic fabric is developed. Dilatant action may tend to restore the equilibrium as already mentioned but if the velocity of the direct partial movement exceeds the rate at which the less competent material of the fabric can be re-organized and shifted in position, then the dilatant action is ineffective. This principle must always be considered in studying relations of direct and indirect partial movement.

The effect of the velocity rule may be seen directly in the 'si' of porphyroblasts. The S-curves, indicating para-tectonic crystallization, have commonly an increasingly sharper curvature from the center to the margin. Assuming a constant growth-velocity, this is accounted for by the increase in

velocity of partial-movement as the porphyroblast increases in size. The form of the S-curves is dictated (1) by the growth velocity of the porphyroblast and (2) by the angular velocity. The first is largely a function of the time and may be considered as constant. The second is a function of the increasing velocity of partial-movement to which a growing porphyroblast is subjected. Assuming this acceleration constant it is thus possible to compute at least minimal values for the amount of rotation of the centre point of the porphyroblast and S-curve. Schmidt (L 18) calculates an average factor of 3, i.e., the absolute movement in a horizon of thickness 'n' is 3n; Becke calculates a factor of 5.6 in one example studied (L 19). Whether one shares confidence in such quantitative measurements or not, their results indicate indisputably the order of magnitude and reality of mechanical movements in tectonites.

Porphyroblast Orientation - The orientation of porphyroblasts has been little studied. From their use as criteria for para-tectonic and post-tectonic crystallization it is obvious that they may form during or after deformation. The generalization that they form exclusively after cessation of mechanical action is not tenable.

The schistosity surfaces of a fabric provide ready-made planes of weakness in which porphyroblasts may grow. The long hornblende laths lying criss-cross in the schistosity of Garbenschiefer have followed this Wegsamkeit, or path of least resistance. The path of least resistance in a tectonite possessing only a linear structure would be parallel to 'b' and a dimensional orientation might form from growth parallel to this

axis. Other cases might be cited of this post-tectonic crystallization in which presence of active stress is not required. In cases in which crystal boundaries or cleavages are visible, growth usually occurs with a prominent crystallographic direction parallel to the Wegsamkeit; in other cases a statistical analysis must be made. Whether or not <u>idioblasts</u> (porphyroblasts with well developed boundaries) are better oriented than <u>xenoblasts</u> (porphyroblasts with poorly developed boundaries) has yet to be shown. The former type has the greater recrystallizing power, which may possibly be expressed in the degree and accuracy of the orientation. Further, rotation of mature porphyroblasts might result in a girdle orientation, corresponding to that developed for B-tectonites.

Porphyroblasts of para-tectonic growth may show an orientation in which a prominent cleavage surface lies parallel to the tectonic axis 'b'. Since the grains are in optical continuity from centre to circumference, only at the time of formation of the nucleus can an orientation controlled by the Wegsamkeit be shown. From then on the axis of rotation of the fabric forms the most important control.

These two cases of post-tectonic and para-tectonic crystallization illustrate in tectonites the presence of <u>growth fabrics</u>, which were mentioned on p. 5 as a subdivision of apposition fabrics. The possibility of growth in tectonites, not only of porphyroblasts, but also in some cases of other elements as well, must always be taken into consideration, as only on this basis can correct interpretation of the fabric be made.

Riecke's Principle - Discussion of this well-known principle, in its possible application to deformed rocks, has been going on for more than 30 years. The famous experiment of applying pressure to a crystal lying in a saturated solution of its own composition, so that it dissolves parallel to, and grows normal to, the stress, has proved intriguing to many geologic investigators. Van Hise and Becke have been the chief proponents of the idea that many foliated rocks have originated simply by grain elongation in response to Riecke's principle, and without mechanical movement. In the light of our present knowledge of tectonites, however, the following points must be considered - (1) Elongation of grains by solution and redeposition means that the schistosity surface formed is parallel to AB of the strain ellipsoid. In this plane no mechanical movement can occur (See p. 77). Evidence of movement from other sources, such as shown by porphyroblasts with rotated 'si' would make this postulate untenable.
(2) The parallel elongation of grains may be due (a) to rotation of originally heterometric elements into parallel position, (b) to a pseudo-dimensional orientation, brought about by lattice orientation (p. 79) (c) to growth of crystals in a schistosity surface. (a) and (b) involve mechanical movement; (c) does not require stress; all three make Riecke's principle inapplicable.
(3) If the recrystallization is accompanied by formation of new minerals, equilibrium may be restored without elongation.

In summary, it may be said that, with our present knowledge of tectonites, the burden of proof rests on proponents of geologic application of this contentious experiment. Cases may be found in which all of the above conditions are satisfied,

but this must be demonstrated by detailed analysis of the fabric.

Comparison with Metal Fabrics - Mechanical working of metal fabrics (particularly steel) yields much information of value to students of rock fabrics. Such mechanical treatment may be carried out 'hot' or 'cold', depending on the product desired. Cold-working increases strength, elastic limit, and hardness of the fabric and decreases the ductility. The space lattices of the elements are disturbed and the grains are distorted and stretched, but without diminution of size. Twinning is commonly developed. Hot-working, following cold-working, causes recrystallization of the grains and restoration of the space lattice. The grain size is at first decreased; then, with rising temperature, is increased. Recrystallization occurs very commonly in the intergranular film and spreads from these surfaces. It is a 'dry' recrystallization and for a monomict fabric the following relations hold -

1. The higher the degree of preceding cold-working, (a) the lower the temperature at which recrystallization will begin, (b) the longer it takes (at the given temperature of hot working) for the recrystallization to work itself out, and (c) the finer-grained is the resulting fabric. (Increasing temperature coarsens the grain as already noted.)
2. After all stresses are relieved, (at the temperature of recrystallization) no further recrystallization occurs.
3. Presence of a second constituent in the fabric may change these relations in amount, but not in character.
4. Original grain size does not influence final grain size when equilibrium is finally established.

Summarizing, therefore, - In a dry recrystallization of a monomict metal fabric the grain size depends only on the degree of preceding cold-working and the temperature. Although details are lacking for rock fabrics, we believe that mechanical working, accompanied by recrystallization, is the most important agency in the formation of a tectonite. An attempt to use grain-size as a criterion for the degree of cold-working has been made by Schwinner. (L 20) By selecting some abundant mineral common to two rocks A and B of uniform, but different grain-size, it is stated that, if A is the finer-grained of the two, it has suffered, before recrystallization began, more mechanical working than B. On this account recrystallization commenced at a lower temperature, and the grain-size of A is finer than that for B. Although the analogy is enticing it leaves para-tectonic crystallization out of consideration, which, from the standpoint of fabric analysis, we believe to be of first importance. The recrystallization in metal fabrics begins, on the contrary, only at a late stage of deformation and is not "para-tectonic."

Some further points of <u>apparent</u> similarity are -

1. Cold-working of metals strains the individual crystals, so that the space lattices are distorted. In rock fabrics calcite and quartz commonly show "strain" shadows. Opinion, however, is not unanimous that the "strained" appearance is not due to microscopic fracturing of the minerals.
2. Recrystallization in the intergranular film. In a metal fabric there is a common tendency for the recrystallization which succeeds cold-working to start in fractures or interstitial spaces and spread from there. In a fabric of strained quartz

crystals or superindividuals, as they are called, it is not uncommon to find smaller unstrained, recrystallized grains in the intergranular film. As both types of quartz show a similar well-defined orientation, the larger strained quartzes (super-individuals) may be interpreted as showing the effect of cold-working and the smaller unstrained ones as having recrystallized from the larger grains under succeding hot-working. This example for quartz is somewhat neutralized by the behaviour of calcite, which, in a similar mixed fabric of large strained grains and smaller recrystallized ones, shows partial loss, through recrystallization, of the accurate orientation of the large grains. No explanation of this difference in behaviour of quartz and calcite is known at present.

3. There is a certain amount of twinning due to mechanical working of a metal fabric. There is indirect evidence of this also from quartz; direct evidence from calcite. The evidence for quartz is statistical and is shown in Fig. 13. The vertical axes form two maxima symmetrical about the main schistosity surface of the rock and about 75° apart. This same symmetry and angular interval has been noted in several other cases, and it is significant that the usually persistent maximum in 'a' is missing in such cases. In measuring, the axes of adjacent grains fall in alternating fashion in the two maxima, which evidence, together with that previously noted, indicates the probability of a rhombohedral twinning. The measured angle of 75° corresponds very well with that for a known twinning of the rhombohedral surface 'r' of quartz, in which $r(10\bar{1}1) \wedge C' = 38^\circ 13'$.

4. The movement-pictures for metals and tectonites are apparently alike - i.e., elongation by deformation takes place in a direction normal to the stress. For metals, however, this is a purely mechanical stretching; in tectonites it probably involves contemporaneous recrystallization (para-tectonic).

The following are two major points of dissimilarity of rock and metal fabrics -

1. Rock fabrics recrystallize commonly with formation of new minerals; metal fabrics do not. This in itself raises a great difficulty in making direct comparisons, as there is no basis for the assumption that the new material will behave similarly to the old.
2. The recrystallization of rock fabric is considered to be 'wet'; that of a metal is known to be 'dry'. The effect of solutions in bringing about recrystallization during the deformation, as we believe is abundantly the case, prevents direct comparison with metal fabrics, in which recrystallization is confined to a later stage of deformation.

Consideration of these apparent similarities and known dissimilarities indicates that, while comparisons are instructive, there is no direct correlation of details possible at present. There are many more variables in a rock fabric than a metal fabric, factors which can not be evaluated properly and concerning which we have no experimental evidence. The general scheme of mechanical working has undoubted application for rocks but as yet too much emphasis on any phase of it is hardly warranted.

Summarizing the discussions (1) on application of Riecke's principle (representing purely molecualr movement) and (2) on application of mechanical working principles for metals (a deformation phase followed by a recrystallization phase) we can only state at present the possibility of their partial application to rock fabrics, and only then in cases in which it is possible to eliminate all negating factors. Caution is the best guide to progress in attempting analogies with the simpler systems of the laboratory, even though direct comparison on certain points appears possible.

Determination of 'b'.

The first goal in investigating a tectonite is determination of the strike and pitch of the tectonic axis 'b'. As already noted (p. 32), 'b' is a direction, usually visible in a specimen and shown by (1) parallel arrangement of unequidimensional grains, (2) the intersection line of two or more surfaces, (3) the axes of folds or parallel crumples. In areal mapping of tectonites, information concerning 'b' is invaluable. The strike of 'b' at different localities may be plotted directly on the map and the pitch may be indicated by varying the length of the strike line - e.g. short for steep pitching axes, longer for axes of flatter pitch. These axial lines as they are called, thus give a graphical summary of the rotation axes, and therefore of the deformation of the region. A glance at such a map will show regional flexures in the axes, the relation of the axes to lithologic units, whether steep or flat pitch is characteristic, etc., all of vital importance to structural interpretation.

Statistical analysis is not necessary in all cases but, since 'b' is not always visible and since traces of a second or even third 'b' may be detectable from the diagram, it is advisable to make the determination. 'b' represents the axis of rotation of a tectonite, both for internal and external deformation (see p.45) and it is fortunate that in so many cases these rotation axes manifest themselves to the naked eye in the three ways indicated above. On the other hand, this megascopic factor should not be depended upon to picture the whole story concerning 'b' axes. Thus, many marbles appear perfectly massive - no trace of a direction is visible in a hand specimen. A statistical analysis of the lamellae, however, gives a diagram in which the poles to these lamellae lie in a girdle, i.e., the lamellae have a common statistical axis of intersection. From analyses of calcite tectonites in which 'b' is visible we know that girdles of this type stand normal to 'b'. We can therefore in this example set up the invisible 'b', represented by the common intersection line of the lamellae, normal to the girdle obtained, and on this basis proceed further with the analysis. Cleavage or schistosity surfaces in a tectonite usually contain a visible 'b', but if not visible, it is quickly found by measurement of the mica in the section. Although a large part of the mica lies sub-parallel to the schistosity surfaces, a statistical analysis shows nevertheless that the poles to the mica plates form a girdle in the diagram which stands normal to the schistosity surface in the rock. As with the previous case of a calcite tectonite we know that 'b' is also normal to this girdle and from this relation we can locate the position of 'b' in the surface. The girdle need not

be completely closed; its parts need only be sufficiently outlined so that they have a common normal, which is 'b'. If mica is not present in sufficient quantity, or shows no indication of a girdle, quartz may be measured. Here also a girdle is the commonest manifestation of the orientation and 'b' stands normal to it. (see Fig. 6) A second 'b' may be indicated by a complete or partial girdle normal or inclined to the main girdle. These are discussed later on p. 81. More measurements may be necessary in such cases than if only one 'b' is present.

In rocks of too fine grain for measurement with present optical equipment, it is possible to determine 'b' from X-ray analysis. Rocks such as slate belong to this class and the general method is outlined on p.27. From experiments on specimens whose 'b' is known (see Figs. 14 and 15) we know the following:- With radiation parallel to the cleavage and further, parallel to 'a' in one specimen and parallel to 'b' in a second, there is a central vertical zone of intensest blackening normal to the cleavage which indicates that the reflections are due, in X-ray parlance, to an oriented powder. An unoriented powder gives rings blackened uniformly at all points. From recent work by Sander (L 21) we believe further that this orientation effect is due primarily to mica; quartz, the other important constituent of a slate, being unoriented in this fine state of aggregation. In Figs. 14 and 15 the <u>angular width</u> of the zone of intensest blackening is different for the two specimens under consideration - greater in Fig. 14 (radiation parallel 'b') than in Fig. 15 (radiation parallel 'a'). This indicates that the variation of

the mica plates from exact parallelism with the cleavage is greater around axis 'b' than 'a' and conforms to all optical experience with coarser-grained tectonites, in which we assume 'b' to be a rotation axis. We have therefore a method of determining 'b' in a slate in which it is not visible to the naked eye. By preparing a series of specimens and setting up the cleavage parallel to the radiation we may determine that specimen whose reflections show the maximum angular width of intensest blackening. 'b' is then parallel to the radiation for this specimen.

Tests indicate that the degree of accuracy with which 'b' may be located by X-ray work is less than with optical methods. Further, if a second axis 'b^1', which gives an angular width of intensest blackening approximately intermediate between 'a' and 'b', lies in the cleavage and approximately bisects the angle formed by 'a' and 'b', the trial method outlined above will probably give no indication of the presence of this axis. Again, the presence of a second, less well developed axis 'b^1' lying parallel to 'a' might not be suspected at all. The method is therefore most reliable for determination of the main 'b' of the fabric.

S-surfaces

S-surface is a term made necessary by the findings of statistical grain analyses. It includes all observed surfaces in tectonites, and in addition statistical surfaces, established by the grain orientation, which are not visible to the eye. This conception of a "surface" invisible to the eye appears on first thought to be incongruous. A surface, as we ordinarily

conceive it, is defined by a parallel dimensional arrangement of flaky or elongated minerals and is developed in varying degree of perfection. The lattice orientation of minerals such as quartz and calcite, which are commonly isometric in outline, indicates, however, "surfaces" in a fabric of which the dimensional arrangement gives no sign. This lattice orientation indicates "surfaces" which are just as genuine as those visible to the eye. To avoid confusion therefore we name all of them, visible and invisible, s-surfaces. Schistosity, cleavage, foliation etc. are therefore included among the visible types of s-surface, but are not synonymous with it. Genetically there are two kinds of s-surfaces -(1) shear surfaces, formed as a result of shearing movements parallel to the surfaces and (2) plaiting surfaces, formed as a result of shearing movements inclined to them or by rotation of material into them. The distinction between these two types is of great importance.

Information regarding s-surfaces (or any other part of a fabric) is best obtained by measurement of 'b' sections (cut normal to the tectonic axis). Examination of three mutually perpendicular sections cut from the same specimen does not always give diagrams which, upon 90° rotation, coincide with each other. The cause for this lack of correspondence lies in inhomogeneities in the grain-fabric which statistical measurement of 'a' and 'c' sections brings out to an exaggerated degree. These inhomogeneities are due chiefly to two things (1) breaking down of superindividuals, or large strained grains and (2) presence of folds and crumples. Superindividuals commonly break down to lens-

shaped masses whose long axes are parallel to 'b' of the fabric. Study of separate lenses indicates their probable origin from a superindividual. The granulation of such a grain results in a group of smaller grains whose orientation is essentially the same as that of the parent superindividual. The best statistical measure of the fabric is (Fig. 17) therefore obtained from that section which includes the maximum number of these lenses. Due to the arrangement of the long axes parallel to 'b', the b-section shows the best profile and is the one to be measured wherever possible.

The same explanation holds for folds and crumples. Their axes are parallel to the tectonic axis 'b' and as a result the most complete profile is seen in a 'b' section. Measurement of this section gives the best statistical picture of the orientation and the most reliable indication of the position of the s-surfaces.

Shear surfaces - In the example of a tectonite described on p. the foliation surfaces represent s-surfaces which, from the orientation of the chief maximum of quartz in 'a' indicates shear surfaces. The general hypothesis of origin is there worked out and need not be repeated here. However, this clear relation of a quartz prism rule and a megascopic s-surface is not always realized and the relation of orientation of different minerals in the same fabric is a necessary prerequisite to interpretation in most cases. It is fortunate that platy minerals such as mica commonly show s-surfaces due to the parallel dimensional arrangement of flakes. In such cases, if statistical

analysis indicates movement <u>parallel</u> to the surface outlined by the mica, we have a shear surface. A conspicuous dimensional arrangement of grains such as mica is not necessary however for the development of a shear surface. A fabric of equidimensional quartz or calcite grains may show by its lattice orientation equally well developed shear surfaces. This is illustrated in the next section.

1. Grain Orientation Correlation

A lime-phyllite studied by Sander shows no megascopic s-surface and only the tectonic axis 'b' is definitely visible. Figures 18, 19, 20, 21, for calcite, quartz and sericite show in each case a girdle normal to the tectonic axis, indicating a B-tectonite. Of especial interest at this point, however, is the arrangement of the different maxima within the girdles. Fig. 18 shows the arrangement of the calcite axes; Fig. 19 the poles to the lamellae of the same grains. Close examination of the two girdles shows, as would be expected, that the pole <u>maxima</u> in Fig. 19 coincide with the axial <u>minima</u> in Fig. 18 and that the angular distance from a lamellae maximum to an axial minimum is 20-30°. Since $C^1 \wedge e(01\bar{1}2)$ is 26° we have in this case <u>statistical</u> evidence of the σ-rule for calcite (p. 36) without actual determination of the angle of 26° for individual grains. The numbers in Figs. 18 and 19 have reference to the maxima and minima. Fig. 20 of the quartz axes shows scattered maxima within the girdle and minima which are numbered similarly to Fig. 19. It is obvious that the axial <u>minima</u> of Fig. 20 and lamellae <u>maxima</u> of Fig. 19 coincide in large part and that the coincidence

is not fortuitous: From this relation we infer a rhombohedral rule for the quartz (see p. 35), indicated by the angle of 20-30° between the maxima and minima. Since direct evidence of s-surfaces is given only by measurement of actual crystallographic directions, it is seen that the control here is the lamellae maxima of the calcite. Without the evidence from Fig. 19 of probable position of s-surfaces (indicated by the statistical positions of the calcite lamellae) it would not be possible to decide in the case of quartz whether a prism or rhombohedral rule was developed.

Fig. 21 shows the maxima for poles to sericite flakes, each maximum numbered for comparison with the maxima and minima in Figs. 18, 19, 20. The coincidence of maxima and minima is further brought out and the relation of - <u>lamellae maxima = axial minima</u> - is firmly established. In this tectonite no s-surface is visible, since the mica is scattered around 'b' and does not develop a conspicuous schistosity surface. The girdle diagrams for quartz, calcite and sericite present united evidence that shearing has been active at one time or another on several surfaces intersecting in the zone of 'b'. These are hol-surfaces, and <u>external</u> rotation about 'b' has brought about development of several successive ones, indicated by the submaxima in each girdle of the three minerals investigated.

2. Shear Zone Tectonites

Data on glide lines in shear surfaces should be obtained and the subject has already been discussed for the prism rule of quartz in the introductory example of a tectonite on p. 38 .

The glide line for different minerals is given on p.   and the statistical effect of these in a fabric constitutes the glide line for the whole fabric under consideration. In tectonites it corresponds to 'a', the direction of transport of material during deformation, and is normal to 'b'. In a B-tectonite it lies parallel to the girdle.

Glide lines have special significance in zones of intense shearing. In contrast to ordinary tectonites, the most prominent direction visible in these fabrics represents the direction of movement 'a'; and 'b', if visible, is not nearly as pronounced. A slickensided surface is a good example of this class of tectonites, in which the most pronounced direction in the surface of schistosity is 'a'. A particularly clear example from such a shear zone is shown in the accompanying figures. Fig. 22 represents a 'c' section of a quartz fabric (parallel to the shear surface); 'b' is the tectonic axis as in an ordinary tectonite; it is also normal to the dimensional arrangement of the grains. These quartzes, moreover, are oriented accurately with their axes normal to 'b' and parallel to the long dimensional axes of the grains. (Fig. 23.) There is no distribution of the vertical axes of the grains in a girdle and the glide line normal to 'b' is pronounced. This is the most pronounced visible direction in this surface; 'b' is indicated only by a faint fibrous structure which in thin section is shown by the parallel arrangement of needles of biotite, hornblende and epidote. From the statistical analysis however it is seen to be not a case of two 'b's', as is common in many cases (p. 81) but of an accurately oriented S-tectonite with glide line 'a' (normal to 'b'). This

[illegible] the

[illegible] effect [illegible]

[illegible] the [illegible] fabric [illegible] [illegible] it

corresponds to 'a', the direction [illegible] of material [illegible]

[illegible] mation, and is normal to 'b'. [illegible]

[illegible]

[illegible] have special [illegible] [illegible]

[illegible] contrast to ordinary tectonites, the [illegible]

[illegible] visible in these [illegible] [illegible] the lin-

[illegible] 'a'; and 'b', if visible, [illegible] as

[illegible] enabled [illegible] [illegible] this class

[illegible]

[illegible] in 'a'. A particularly clear example from

[illegible] accompanying [illegible]

[illegible] 'a' [illegible] (parallel to [illegible]

[illegible]

[illegible]

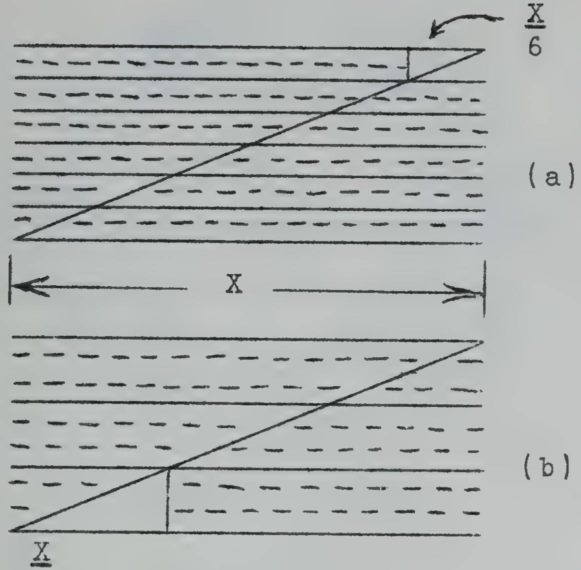


Figure 12 p.51

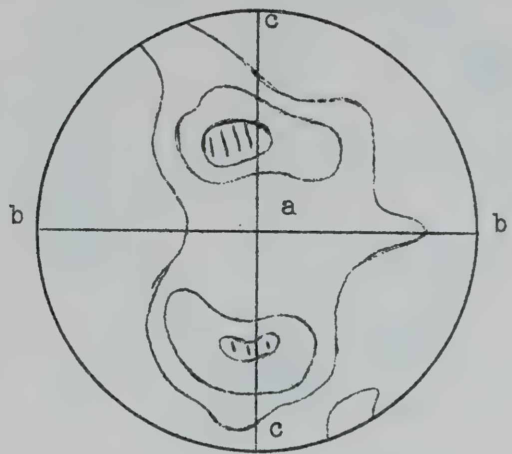


Figure 13 p. 58

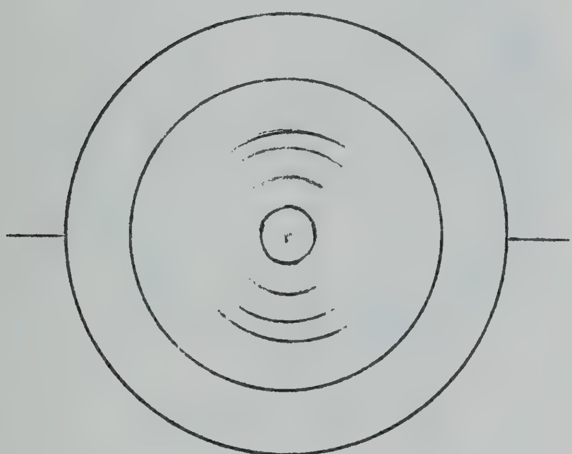


Figure 14 p.62

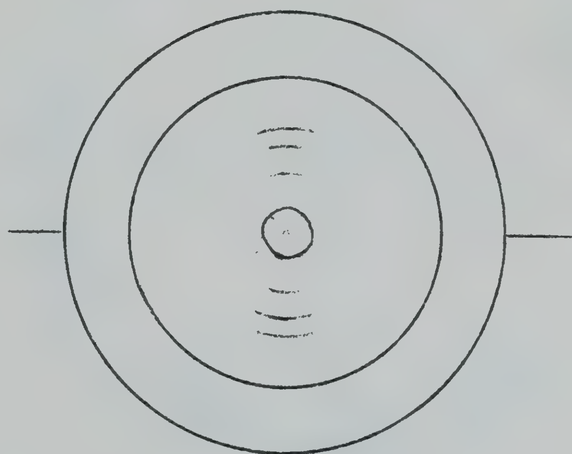


Figure 15 p.62

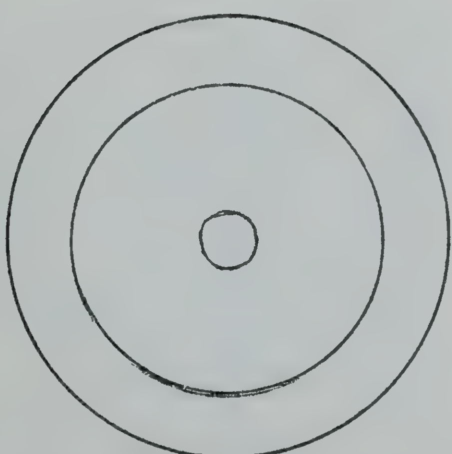


Figure 16 p.80

Figure 17 p.65

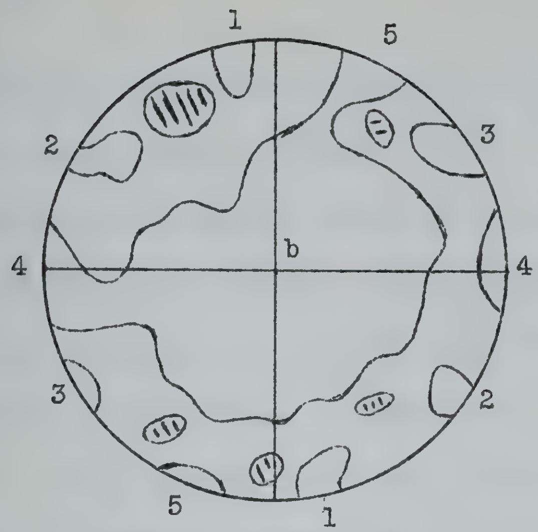


Figure 18 p.66

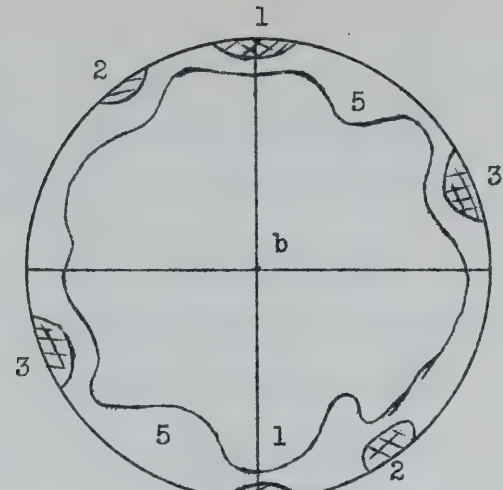


Figure 19 p.66

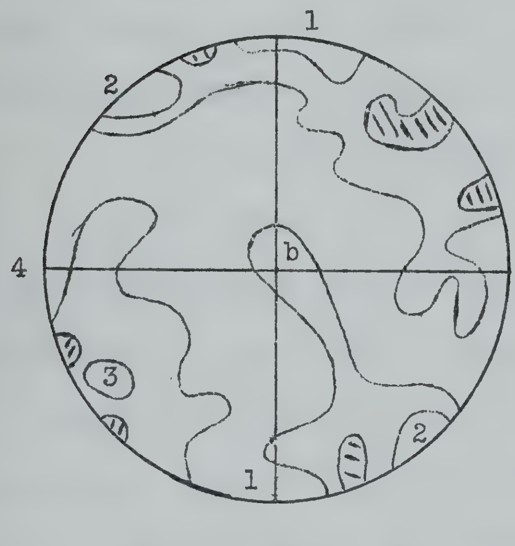


Figure 20 p.66

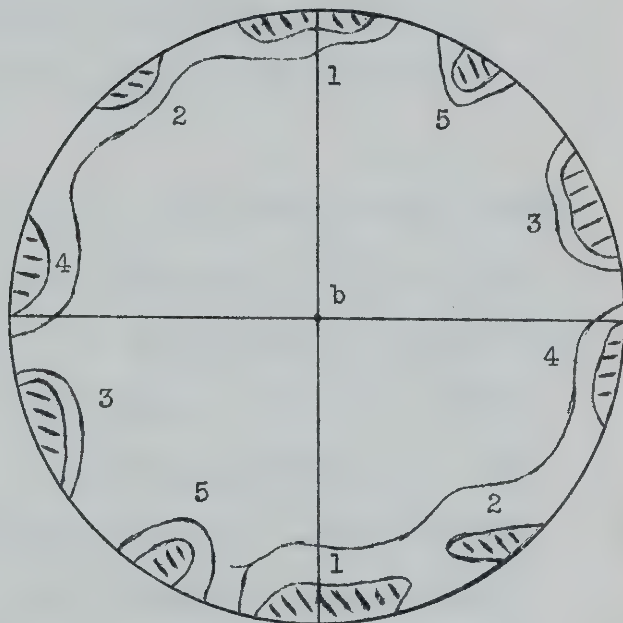


Figure 21 p.66

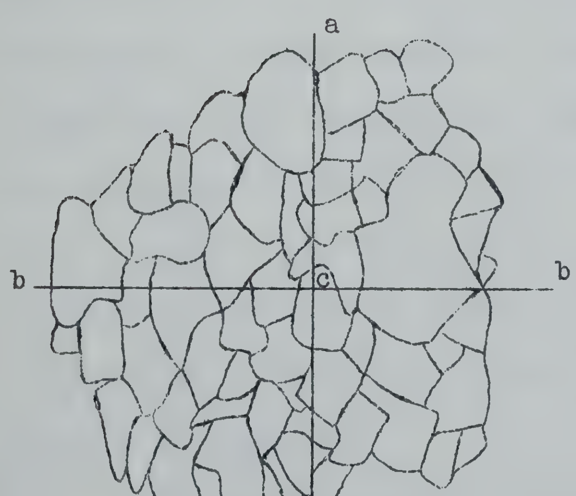


Figure 22 p.68

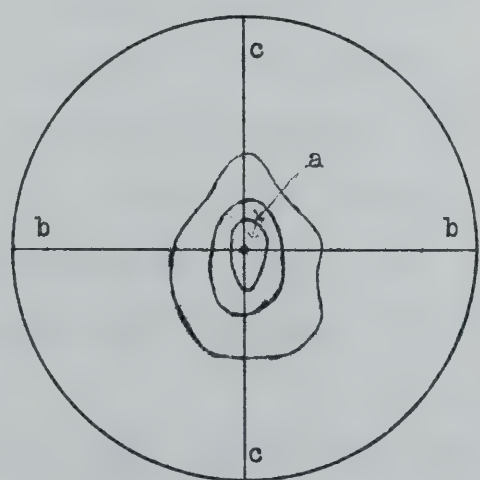


Figure 23 p.68

distinction is characteristic of zones of intense shearing and all such zones, whether real or only suspected, require careful statistical investigation on account of their importance in structural problems. The grain elongation normal to 'b' rather than parallel to 'b' is significant in connection with the discussion on p. 46 . There the combination of girdles normal to 'b' (indicating external rotation) and grain elongation parallel to 'b' was explained as due to the ineffectiveness of the combined internal and external rotations in causing elongation of individual grains normal to B.

The grain elongation normal to 'b' in these shear zones, on the other hand, involves little or no external rotation. One single maximum is ordinarily formed in 'a' and there is no girdle. Following up the earlier hypothesis, this means that the A axis of strain is effective in such cases in causing elongation. The planes of least distortion form presumably a small acute angle with A and therefore the sections of the elongated grains which are visible in the shear surface of the rock represent the actual elongation fairly exactly. The lack of external rotation (and therefore lack of a girdle) may be due to greater velocity of of deformation in these zones. In any case, the coincidence of 'ac' girdles and elongation parallel to 'b' in ordinary tectonites, and absence of girdles and elongation normal to 'b' in shear zone tectonites is one of the fundamental findings of this method of analysis.

Many surfaces of this shear zone type are of too fine grain to be studied optically, and X-ray analysis is necessary. Since the important thing is to determine the glide line in the

surface, radiation is passed through a specimen normal to the shear surface rather than parallel to it, as when 'b' is determined (p.62). The orientation shown by the grains will cause certain reflections to be concentrated on certain places in the rings. These points of intensest blackening form a diameter or band and the symmetry plane of the specimen is parallel to this symmetry plane (cf symmetry of example on p.62). The criterion necessary to determine 'b' (p.63) may not hold for this type of shear surface, but if it does, it may be used as a check on the glide-line determination ('b' normal to the glide line). It is not definitely established just how sensitive this method is in determining glide lines; i.e. whether the glide line of an ordinary tectonite might be so established. 'b' is so easily determined, however, that glide line determination is less often necessary. Fig. 16 illustrates a case in which the radiation was passed through a specimen of slate normal to the cleavage. The rings are equally blackened at all points. No glide line is indicated and the cleavage surface is interpreted as due to "plaiting",and not directly to shearing (p.80).

3. Swinging of Glide Lines

A common characteristic of glide-lines is that of oscillating symmetrically about 'ac'. Fig. 24 illustrates this effect for quartz. Nine tectonites are summarized in it and each point represents a maximum. These maxima do not lie <u>in</u> 'ac' but symmetrically on either side. Whether prism or rhombohedral rules are developed is unimportant at this point; the significant factor is that the individual quartz glide lines swing out of the

main gliding zone 'ac' symmetrically on either side, but without destroying the girdle form. This type of movement, although on a smaller scale than rotation about 'b', is equally characteristic and forms part of the main movement-picture of the deformation. Its interpretation in terms of shear surfaces can not be fully evaluated at present, and it is not further discussed here.

4. Analysis of 'si' fabrics

The analysis of a 'si' fabric in porphyroblasts may permit important deductions to be made regarding the deformation. Thus, if the orientation shown by the grains of 'si' has the same relation to the foliation surface as the orientation of the grains in the adjacent 'se', it may be inferred that the deformation, whether before, during, or since growth of the porphyroblast, is the same in character. If, however, the orientations of 'se' and 'si' do not correspond, it is justifiable to assume some change in the character of the deformation. Special cases of 'si', such as S-curves, (p. 50) can be dealt with individually and may bring out important details.

5. Relative Movement

Relative movement in shear surfaces is important, and megascopically the criteria for its determination are well known (L 22). Statistical data are also available in a number of cases and have added value in the event that field observations are lacking. Fig. 25 illustrates an example. In the centre is shown the girdle orientation of cleavage poles of large biotite holoblasts of a crystalline schist; at the margin is γ' for small muscovite

flakes. γ' is measured with a Berek compensator and, since γ for muscovite is parallel to (001) and normal to (010), the determination of γ' for each flake gives approximately the arrangement of the cleavage flakes. The positions of 'b' and 'a' are established therefore by the maximum for γ'. Since the glide-plane for muscovite is (001) and the glide-line is parallel to (010), 'b' is parallel to the γ' maximum, and 'a' is normal to it in the surface of schistosity. The biotite cleavage poles lie in a girdle normal to this 'b'. The maximum indicates, however, that the cleavage flakes do not lie exactly parallel to the surface of schistosity, but slightly inclined to it. Since the muscovite shows a glide-line (parallel to 'a'), the s-surface in which it lies is definitely a shear surface, and the average position of the biotite holoblasts indicates an imbricate structure with respect to this surface. The geographic co-ordinates NS-EW on the diagram give the direction of relative movement in the shear surface; in this case (since the diagram represents the <u>lower</u> half of the projection sphere) "top" moves from SW to NE with respect to "bottom". The orientation of the biotite holoblasts in this statistically imbricate arrangement may be due to their relative slowness in adjusting themselves parallel to the shear surface, in any event their position indicates the nature of the relative movement.

6. Residual Orientation

The development of shear surfaces may in some cases result in orientation of mica which is apparently contradictory to the movement-picture of the deformation. Thus in Fig. 26 is

shown a girdle of biotite cleavage poles which lies approximately normal to the tectonic axis 'b' of the rock. The foliation surface (defined by the micas) is parallel to 'ab' and the chief maximum of cleavage poles lies therefore 90° distant from it. The biotites measured were small flakes and shreds, and their orientation represents the normal condition. Fig. 27 shows the orientation of large biotite holoblasts from the same section. The figure has the same orientation as Fig. 26 but the biotite orientation is distinctly different. The cleavage poles form a girdle which lies normal to the one in Fig. 26, with a point of intersection marked approximately by the maximum in the lower half of the diagram. That is, a small majority of the holoblasts lie approximately in the foliation plane; the remainder, however, lie in a "cross" girdle 'bc'. The direction of movement in the foliation surface is parallel to 'a' and the orientation of the small biotite shreds around the tectonic axis 'b' (Fig. 26) fits in with this picture of the set-up. The large holoblasts of Fig. 27 represent in all probability those grains which were unfavourably situated with respect to the direction of movement 'a' and rotation axis 'b'. They have escaped the major deformation and represent a residual orientation. Those which originally lay in the neighbourhood of the surface along which the main shearing took place were oriented so as to form the cleavage pole maximum in the lower part of the diagram. Those which lay in other positions in the 'bc' girdle were not affected to any extent by the deformation. The size of the grains may be due to growth by crystallization, made possible by their unfavourable orientation with respect to the direction of shearing and

axis of rotation.

7. Intersecting Shear Surfaces

Shear surfaces have been described thus far without reference as to whether one or two sets may develop as a result of any one deformation. Fig. 7 illustrates the manner in which the general case of rotational strain favours development of one set of shear surfaces - a deduction which corresponds with field observations. The less favoured "wedge" of Fig. 7 represents a zone which, in rock deformation, may show as a poorly defined foliation surface or simply as a fracture surface caused by shear, but not involving necessarily a correlated lattice orientation of the grain fabric. An example illustrating a combination of shear fracture and lattice orientation is shown in Fig. 28. The tectonic axis 'b' of the rock is normal to the plane of the diagram. In the center is sketched (with the same orientation to the diagram) a band of small quartz grains which lie in a large single crystal. The layer of quartz grains is offset partially by fractures cutting across it as shown. Measurement of the quartz in this layer shows the axes to be oriented in two maxima. The stronger one is sub-parallel to the band in which the grains lie; the weaker one is sub-parallel to the fractures cutting through the layer. Two assumptions are possible (1) that the two maxima were formed at different times and (2) that they are contemporaneous. Assuming the latter to be the case we see that the thin "wedge" of Fig. 7 would lie approximately parallel to the band of quartz grains and the stronger of the two maxima; the thick "wedge" would be correlated to the

fracture system and the weaker of the two maxima. Since the fracturing does not entirely offset the quartz layer it is seen that contemporaneous orientation of the quartz into the two maxima is quite possible with the interpretation given.

8. Schmidt - Sander Hypotheses

On a regional scale, Schmidt (L 23) has outlined an hypothesis of the development of shear surfaces which deserves attention. There are three stages - (1) A period in which a number of shear surfaces are developed without any individual surface achieving predominance. This represents the stage in which the fabric elements are still striving to adjust themselves to the deformation by rotation and gliding. (2) A period in which one shear surface achieves dominance over all others. This represents the stage of best adjustment of the fabric elements to the deformation. (3) A period of "braking" in which the resistance to further shear along this predominant surface increases to such a point that further movement takes place most easily along other surfaces inclined to it. This stage would resemble (1) in appearance, but be unlike it in origin. Schmidt emphasizes shear surfaces as representing planes of least distortion, particularly in the initial and final stages. They are "compromise" surfaces, developing at the beginning and end of a deformation in response to restricted freedom of movement parallel to any one surface. Many details are lacking in this general hypothetical picture and it is probably seldom carried through to completion. A more specific hypothesis of shear surface development is proposed by Sander, who considers

the problem from the standpoint of the grain fabric. A passive orientation process may in general be considered from the standpoint of the strength-anisotropism, and internal friction of the structure. Since most rocks are strength-anisotropic they possess variable moduli of elasticity E. ($E =$ load in kg./sq. cm. required to produce 1% linear shortening in a body) The relation of the internal friction F_i to these moduli, determines the degree D_o and accuracy A_o of the orientation. Assuming an unoriented fabric of one mineral and maximum and minimum values of E for this mineral, the following cases then arise.

1. $F_i < E_{min.}$ There is no orientation or grain deformation. Only grain rotation and rupture are possible.

2. $E_{max.} > F_i > E_{min.}$ There is rotation of those grains which are not yet favourably placed for translation; translation of the remainder which are already in favourable position. D_o and A_o are therefore high. A_o is highest when F_i is only a <u>little</u> greater than $E_{min.}$ (rotation is still easy at this stage), and decreases as F_i moves closer to $E_{\cancel{min}\,max}$

3. $F_i > E_{max.}$ No rotation is possible; only grain deformation. Riecke's principle may be applicable here. There is no orientation.

Orientation occurs therefore under the conditions of (2) that $E_{max.} > F_i > E_{min.}$ Further, $A_o \propto \frac{F_i}{E_{min.}}$; i.e., the accuracy of the orientation varies directly as the ratio of F_i and $E_{min.}$

This hypothesis is broader in its scope than that of Schmidt, but conveys essentially the same idea that the grain orientation reaches a maximum, both as to degree and accuracy, only after an initial period of adjustment. The final stage (assuming continued deformation) is reached when grain orientation, shear surfaces, etc. are retrogressive and may conceivably be obliterated entirely.

<u>Plaiting surfaces</u> - In contrast to shear surfaces, plaiting surfaces are formed largely by a dimensional orientation of the grain fabric. A plaiting surface is thus always an <u>observable</u> structure, whereas a shear surface need not be so. The dimensional orientation (forming the plaiting surface) may involve (1) rotation of heterometric grains into parallel position, or (2) lattice orientation of others which are "plaited" into an observable surface. A plaiting surface is assumed to represent mechanically the AB plane of the strain ellipsoid (containing the greatest and intermediate axes), and it is therefore a surface parallel to which shearing movement can not take place. "Flow" cleavage, as interpreted by Leith (L 1), is a system of plaiting surfaces insofar as the above criteria are fulfilled. A statistical analysis is necessary however to distinguish shear and plaiting surfaces with any certainty.

Although direct evidence of the first criterion above (rotation of heterometric grains into parallel position) is not rare (see Fig. 38), it is more difficult to establish the surface as a plaiting surface from this evidence alone. If shearing is going on in the fabric it interferes with the rotation so that

many grains are held in the shear surface and their theoretical final position in AB is never attained. The plaiting due to rotation has its ideal development during the first stage of the scheme of orientation outlined on p. 76; i.e., when $F_i < E_{min}$. Assuming heterometric elements, there is no shearing under these conditions and therefore no interference with pure rotational movements. Rod-like elements tend to arrange themselves in AB with their long dimensional axes parallel to the tectonic axis 'b'. Platy elements tend to arrange themselves in AB without definite orientation with respect to 'b' (Cf. Fig. 16)

Evidence of the second criterion (plaiting of grains into an observable surface by lattice orientation) is given by statistical analysis and has been established in a number of cases. Fig. 29 illustrates an example from a calcite tectonite. The rock has a breaking surface parallel to 'Ab', which in thin section corresponds to the parallel arrangement of the long dimensional axes of the grains. Measurement of the cleavages (one to three per grain) and plotting of their poles gives two maxima within the customary girdle. That is, there are two preferred positions, statistically, in which movements parallel to cleavage surfaces can take place. a' and a" represent these two positions. They lie inclined to 'Ab', therefore inclined to the grain elongation and inclined to the breaking surface of the rock. The inference is that actual movement has taken place by gliding, which is concentrated approximately equally in two positions (parallel to a' and a") and that the net effect is an

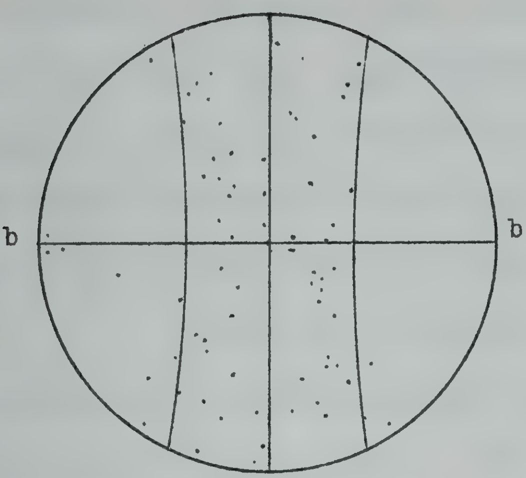


Figure 24 p.70

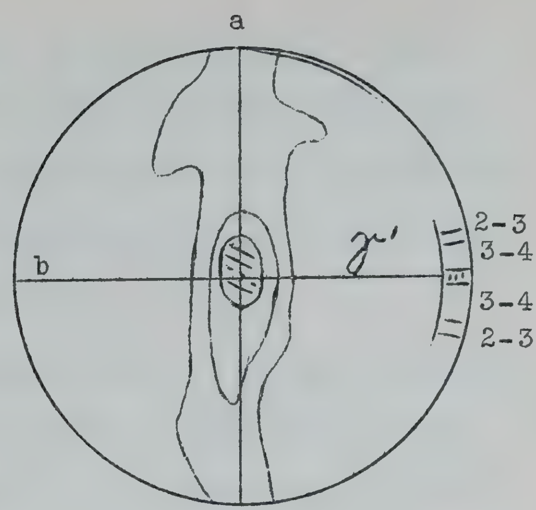


Figure 25 p.71

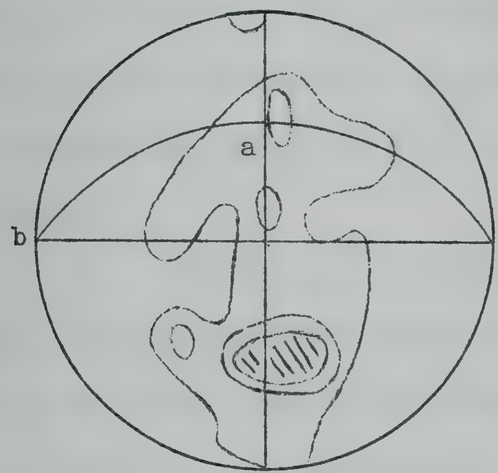


Figure 26 p.73

Figure 27 p.73

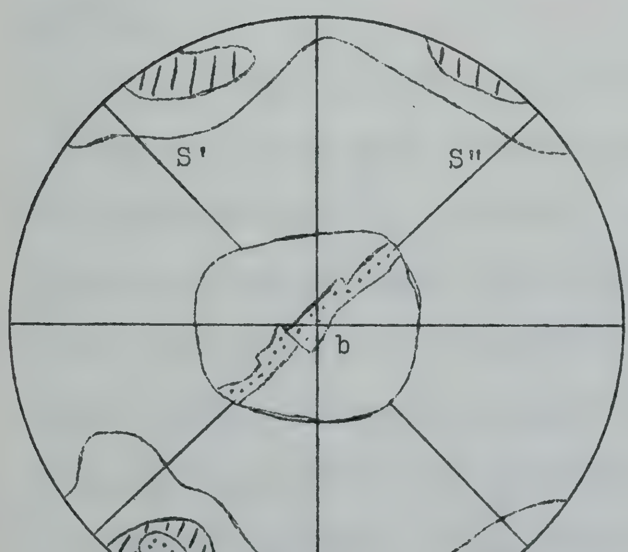


Figure 28 p.74

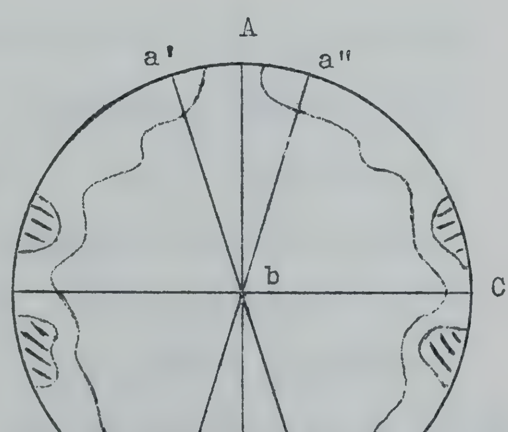


Figure 29 p.78

elongation of individual grains parallel to the bisectrix of a' and a". Had only one preferred gliding direction been developed, the best breaking surface of the rock (cleavage) would be parallel to this direction. With two directions developed, as in Fig. 29, a plaiting surface is formed parallel to 'Ab'.

In terms of the strain ellipsoid Fig. 29 is most easily explained by correlating a' and a" to planes of least distortion and the plaiting surface 'Ab' as parallel to the AB plane. (A in Fig. 29 is A of the strain ellipsoid; 'b' is B.) A represents the elongation, C the shortening of the fabric. Similar examples are known for quartz, in which the crystallographic axes are oriented inclined to a plaiting surface formed of elongated grains.

Plaiting by lattice orientation, as illustrated by Fig. 29, gives the effect of a pseudo-dimensional orientation, but not of a true dimensional orientation. The two types must be carefully distinguished in investigating a fabric, since one is a result of lattice orientation, the other entirely independent of it.

Plaiting surfaces have not frequently been encountered in the analyses made thus far and their importance may therefore be underestimated. A recent investigation (L 24) indicates the possibilities of their development on a regional scale. Many more analyses will be necessary, however, before they can be as accurately evaluated as shear surfaces. The latter possess a statistical glide line parallel to 'a', which is indicative of the preferred direction of gliding in the glide planes of the individual minerals. (Cf. Fig. 6). Plaiting surfaces do not possess

a glide line, since no movement occurs parallel to them. (Cf. Fig. 16) This is the best statistical criterion for distinguishing the two types. Identification of plaiting surfaces merely by observing the elongation of minerals is not reliable, since the elongation may be parallel either to the B or A axis of strain (pp. 46,69). This applies likewise to the elongation of pebbles in a conglomerate, and the deformation of fossils, both formerly considered as certain criteria for recognizing the A axis of strain. The investigations made thus far indicate that the problem is not so simple as supposed, and that the effective elongation takes place more often parallel to B than A.

Further, a system of surfaces which formed originally due to plaiting may at a later time become the locus of shearing movements, or vice versa, and a statistical analysis may give indications of both. Mica plays an important role in such "combination" surfaces due to its platy character. Through rotation it tends to be plaited in the AB plane of strain; in the presence of strong shearing movements, however, much of it is caught up in shear surfaces and rotates no further. Later recrystallization may remove all traces of deformation and only a study of the orientation (to determine presence or absence of a glide-line) will give any evidence as to whether the flakes lie parallel to a shear or to a plaiting surface. Absence of a glide line, however, is not decisive, for later recrystallization may have been accompanied by sufficient movement and new growth of material to obliterate a pre-existing glide line. The determination of plaiting surfaces is thus fraught with difficulties

which cannot be ignored in any modern investigation. Full information concerning the grain and joint fabric and of folding must be obtained in order to draw reliable conclusions.

Crossed Strains

The importance of the tectonic axis 'b' as an axis of rotation in tectonites has been repeatedly emphasized thus far. Rotation around 'c', shown by swinging of glide lines, has been also described. A third characteristic rotation occurs about 'a' as an axis; and it will now be discussed.

In the typical girdle tectonite the symmetry of the grain orientation with respect to the megascopic fabric is expressed usually as monoclinic (See Fig. 19) or less commonly as rhombic (Cf. Fig. 13). That is, in Fig. 19 it is possible to divide the girdle symmetrically in only one way - by passing a plane through it approximately parallel to the plane of the drawing. Fig. 13 may be divided symmetrically in three ways (very approximately) and these planes are represented by the fabric planes 'ab, ac, bc'. The orientation of many diagrams, however, is such that either no symmetry plane is present or the symmetry plane does not coincide with that of the megascopic fabric. These triclinic forms express in varying degree the rotation about 'a' as noted above.

Three diagrams representing phases of this rotation are shown in Figures 30, 31, and 32. The triclinic symmetry of of Fig. 30 is clear; it represents an incomplete 'ac' girdle which is interpreted as having formed originally by the main

strain acting about 'b' as a rotation axis. In addition, however, there has been a small amount of rotation around 'a', shown by the deviation in the contours in the NW quadrant. The monoclinic symmetry of the 'ac' girdle is thus disturbed and triclinic symmetry results. Fig. 31 shows another phase, more advanced. An 'ac' girdle is present but rotation around 'a' has caused some occupation of the 'bc' zone. This is shown by the unsymmetric spreading of the girdle in the N and S sides of the diagram, which results in a triclinic form. A further phase is shown in Fig. 32. There is no trace of the common 'ac' girdle and only a concentration of quartz axes in 'a' suggests that it may formerly have been present. The majority of the axes occupy a 'bc' girdle normal to 'a', similar in all respects to the more common 'ac' girdle. The symmetry of the diagram is monoclinic, but, since its symmetry plane (parallel to 'bc') does not coincide with that of the megascopic fabric (parallel to 'ac'), the total symmetry is still triclinic as in Figures 30 and 31.

The three examples given are not to be taken as successive stages in the development of a 'bc' girdle from an 'ac' girdle but only as indicative of typical phases of its development. Other forms are also known in which the rotation is represented by two girdles intersecting in 'a' (Okl-girdles). One Okl-girdle may be present with a scattering of axes in the 'bc' zone. All represent phases of the disturbance of the monoclinic movement-picture (having the tectonic axis 'b' as axis of rotation) by rotation around 'a'.

Thus far we have considered "rotation" around 'a' in only a general way. Rotation however is of two kinds, internal

and external (Cf. pp. 46,69). Figures 30 and 31 probably represent only external rotation of grains out of the 'ac' girdle, by a stress applied approximately normal to 'a'. On the other hand, the presence of a complete 'bc' girdle with definite maxima requires the same interpretation as has been set up for 'ac' girdles, i.e., a combination of internal rotation (rotational strain) and external rotation. The maximum in the northeast quadrant of Fig. 32 is a characteristic feature of 'bc' quartz girdles and represents a definite lattice orientation. We have, therefore, as this introduction shows, a "crossed" strain, which is indicated by 'bc' girdles in various degrees of development and which have 'a' as axis of rotation. At this point we turn again to Schmidt's example of tectonite orientation (Fig. 6) upon which was built the hypothesis of the main strain.

At the top and bottom of Fig. 6 the 'ac' girdle is supplemented by extensions of the contours in the 'bc' zone. In the light of the discussion above it is obvious that these are best interpreted as evidence of a crossed strain. The maximum at 'c' is not satisfactorily explained and, except in this example, is rarely found. Schmidt believes that it represents translation in 'ab' of basal planes of the quartz grains. Since it is possible, however, that other shear surfaces in addition to the observed 'ab' shear surface are present, a translation parallel to basal planes is not necessarily the only explanation of the concentration of quartz axes in 'c'. The elongation of the contours in 'bc' is probably a result of the crossed strain, whatever the translation-rule of the grains may be, but the maximum may originally have developed at 'c' as a part of the 'ac'

girdle. Further, the grains whose axes are oriented in this incomplete cross girdle are mostly of large size. This may be significant as indicating that the cross strain was a minor feature which did not affect the main mass of grains of smaller size.

The mechanics and time relations of crossed strains have not yet been investigated sufficiently to allow any general interpretation. The occupation of the 'bc' zone in the same manner as the 'ac' zone is significant however and can not be considered as accidental. For 'ac' girdles 'b' is a rotation axis and axis of intersection of possible shear surfaces. Thus the two strains act perpendicularly to one another. An interpretation which might apply for example in Fig. 6 and similar cases is as follows - The 'ac' girdle orientation forms initially as the expression of a monoclinic deformation, having an axis of rotation 'b' parallel to the observed linear structure of the rock. The hypothesis set up for this strain (p. 43) assumes 'b' to be parallel to the intermediate axis B of the strain ellipsoid. From this point on B is now assumed to continually lengthen so that it eventually exceeds A (the initial long axis) and a new orientation of the planes of no distortion becomes necessary. The cases investigated thus far indicate that 'a' of the chief shear surface becomes the new axis of rotation. The new positions of A and C are not necessarily known. This transformation of the strain axes becomes possible if the chief stress, acting initially parallel or sub-parallel to the 'ac' fabric plane, decreases to such an extent that the axial ratio of the strain axes $A > B > C$ changes to $B > A > C$, so that the

direction of shearing finally lies parallel to 'b' (B). Since 'ab' is an existing plane of weakness it probably influences the new orientation of the strain axes and is responsible for development of a girdle parallel to 'bc', which, according to the earlier hypothesis, contains the greatest and least axes of strain.

The development of this girdle is shown in some of its phases by Figures. 6, 30, 31, 32, and seldom reaches completion. In most cases only a small percentage of the grains are included in its development. The crossed strain which forms it may be pictured as alternating rhythmically with the main strain due to fluctuations in the stress conditions. Visible evidence of it may be found in cross folding, cross fracturing, etc. Evidence is also obtained from experiments with paraffin-coated rubber sheets. The chief result is the establishment of the crossed strain as <u>normal</u> to the main strain, from which is postulated a rhythmic alteration of the two, rather than complete independence of action. In cases in which the crossed strain is not normal to the main strain, complete independence of action may be justified in the interpretation. These have been less often encountered in petrofabric investigations, whereas indications of rotation around 'a' (Figures 6, 30, 31) up to formation of a complete 'bc' girdle (Fig. 32) are well known. In either case the symmetry is triclinic in contrast to the monoclinic or rhombic symmetry of the main strain.

The movement in a tectonite may be aptly compared in general (not in mechanical detail) with the flowing of a stream

having parallel banks, an even bed, and a uniform gradient. The main direction of flow corresponds to 'a' of a tectonite, which is interpreted as the average translation direction of the grains in tectonites. Friction between the flowing particles, with or without aid of any unevenness in the bed, causes a rolling movement around an axis normal to the direction of flow. This corresponds to the tectonic axis 'b' of tectonites, which is interpreted as an axis of rotation, both for the strain and the external movement. Bends in the stream cause deviations from the general direction of 'a', which in a tectonite corresponds to rotation around 'c'. These have been described (p. 70) under swinging of glide lines. Lastly, tributary streams entering the main stream normal to its direction of flow set up cross currents which correspond with the crossed strains and rotation around 'a' just described. Streams entering at other angles would set up cross currents comparable to cross strains of probably independent origin.

The relation of the typical maximum in the 'bc' girdle of Fig. 32 to other quartz maxima of tectonites is shown in Fig. 33. The maxima of 19 tectonites having particularly accurate grain orientation are shown here as single points and occupy four distinct areas in the diagram. Maximum I at 'a' is the most common and may occur either alone or accompanied by others. Maximum II may be in many cases due to twinning, especially if maximum I is lacking. Maximum III is the result of a crossed strain as just described. Maximum IV, despite its position midway between II and III is believed to be of independent origin

and not a transition between its two neighbours. Although details of the development and exact significance of these maxima are lacking in most cases, the facts of their existence and relative positions are now fairly well established.

Rupture and Joint Surfaces

The discussion thus far has considered only deformation as expressed by the orientation of the grain fabric. This phase of rock deformation is brought about by partial-movements, i.e., by slow, creeping movements as a result of which the fabric elements have time to adjust themselves by rotation, translation, and recrystallization, without essential change in volume. In contrast to this phase is a deformation in which, due to various factors, these slow adjustments of the grain fabric are not possible and rupture occurs with consequent increase in volume. Statistical analysis of all joint surfaces by field mapping and microscopic study is an essential part of a thorough regional study, since it is now known that the majority of ruptures bear a symmetrical relationship to the fabric axes 'a, b, c'. This relationship is of great importance.

The only classification of joints of interest in the study of tectonites is one which brings out the contrast between shear (compression) and tension joints. This is a fundamental distinction, but one which, without knowledge of the orientation of the associated grain fabric may be impossible to make.

Shear Joints - In the field shear joints will be recognized by any of the criteria which indicate relative movement. They are

termed faults if any considerable movement has taken place. With regard to the main strain and the common crossed strain just described, shear joints may have the following orientations with respect to the fabric axes.

(1) Any orientation parallel to 'b' (therefore 'h0l' planes) except the two positions in which the strain axes of elongation or shortening lie. (Cf. Fig. 8) In all these positions rupture by shear is possible under given circumstances, and may be correlated with the grain orientation. In Fig. 7 the difference in angular opening of the shear 'wedges' for rotational strain means that rupture is more likely to occur in the direction of the wider one. The fabric elements have less chance to adjust themselves with respect to this shear direction, since the movements in this zone are less concentrated in one surface than is the case with the thinner 'wedge'. Fig. 28 is a case which may have this interpretation. Shear joints can be correlated with the grain fabric fairly easily if they occur as 'h0l' planes (as here) since 'b' is the axis of rotation for the main strain and the 'ac' girdle is almost invariably present to give the symmetry.

(2) Any orientation parallel to 'a' (therefore 0kl planes) except the two positions in which the strain axes of elongation and shortening lie. These joints come under the heading cross joints etc., and are related in their symmetry with a crossed strain. They may be correlated either directly with a 'bc' girdle or, by reason of their right-angle orientation, with an 'ac' girdle. A crossed strain may be expressed much more clearly in the <u>joint</u> fabric than in the <u>grain fabric</u>, a factor which makes the importance of field mapping of joints of added importance.

(3) In addition there are joints whose lines of intersection are vertical or nearly so. These can form only if lateral relief is greater than upward relief and may have two interpretations. (a) If their intersection lines are normal to 'b' they probably represent a crossed strain having 'c' as rotation axis (therefore hk0 planes). There is no certain evidence of grain orientation connected with such a strain (indicated if present by an 'ab' girdle), but it is entirely possible that a second crossed strain of this orientation may exist and be expressed only in the joint fabric. (b) They may result from the main strain in cases in which 'b' is vertical. The problem would be settled if 'b' were actually observed in this vertical position. If 'b' is not to be seen in either horizontal or vertical position then reliance must be placed on the orientation of a mica or quartz girdle to determine the symmetry of these vertical joints.

Independent shear joints (hkl planes) will have no symmetrical relation (triclinic) to the grain orientation and girdles. Cases of this type can be established by field mapping and Universal stage analysis.

<u>Tension Joints</u> - Tension joints are much more restricted than shear joints in the positions which they may occupy with respect to the fabric and strain axes. Only two sets are common and, since they are oriented normal to directions of elongation of a tectonite, their recognition in statistical study is of the greatest importance.

(1) '<u>ac</u>' joints are the most abundant tension joints known, and are so named because of their orientation parallel to the 'ac' fabric plane and girdle. They are also parallel to the AC strain

plane and may be termed AC joints. In the field these joints are recognized in a great variety of rocks and usually form the master joints of a formation. They are more persistent than conspicuous, and for this reason have been underestimated in field mapping. It is now known that most joints occuring normal to fold axes or linear structures (both of which are tectonic axes) are 'ac' joints. If 'b' is not easily visible and detailed mapping indicates a persistent set of master tension joints of approximately constant strike and dip, then it may be concluded (provisionally) that the tectonic axis 'b' is normal to this set of joints. This is an important field criterion in all cases in which tension joints are easily distinguished from shear joints.

Joints of the 'ac' type are found microscopically in 'a' sections (i.e. a section cut parallel to 'b') and occur in quartz as fine, hair-like, roughly parallel fractures which cut through the grains independently of their lattice orientations. This is illustrated in Fig. 31 by the orientation of a number of quartz grains (axes in centre) in comparison with fine 'ac' fractures cutting them (poles to fracture surfaces at 'b'). The axes coincide approximately with 'ac', but the joints are not dependent on the positions of the single quartzes and are oriented in 'ac' much more exactly than the axes. Statistically there is a common symmetry of joints and axes; for individual grains there is none.

In terms of the strain ellipsoid these 'ac' joints are parallel to AC of strain, in accordance with the hypothesis already set up for the grain orientation. (See p. 43) The exact

positions of A and C are in most cases unknown and unessential; the important fact is the orientation of these tension joints normal to 'b'. This axis we have already discussed as the direction of <u>effective</u> elongation of most tectonites, despite its parallelism with the intermediate axis of strain (Fig. 8). This orientation of the most persistent and abundant tension joints supplements the conclusion already reached that the direction of the linear structure of tectonites represents actual elongation in the grain fabric.

These joints are undoubtedly related in origin to the main grain orientation and the interpretation of the one is also the interpretation of the other. One reasonable interpretation is that, (1) since there is stretching parallel to 'b' (direction of the linear texture), the joints are contraction cracks which form at a late stage of deformation, after all deformation by partial movement has ceased. They would thus lie parallel to the AC plane of strain. (2) They may form as a result of a crossed strain in which the strain axes are re-oriented so that B is parallel to 'a'. The former AC plane of strain is now BC and, under suitable conditions, tension joints would form parallel to it. (3) They may form in some cases <u>during</u> the deformation without a crossed strain being necessary. This interpretation is based on a well-known laboratory experiment which deserves more recognition than it has received. A test cube of limestone or some other rock is coated on its top and base with a stiff lubricant such as wax or graphite, and pressure is applied normal to these surfaces. Instead of fracture by shear developing inclined to the direction of pressure, a series of

parallel tension joints forms parallel to it whose orientation depends on the direction of maximum elongation of the cube. The lubricant acts so that slipping can occur between the piston of the testing machine and the surface of the specimen and, since rocks are weakest under tension, tension cracks form normal to the direction of easiest relief, or greatest elongation. If tensional forces were applied in the usual way the cube would rupture in one place only, in the same way as a wire cable. The analogy with formation of 'ac' joints in tectonites would then be as follows - Incompetent beds enclosing more competent ones may represent the same type of set-up. The joints would develop in the more competent material due to sideward slipping allowed by the "lubricating" action of the incompetent material. Examples of 'ac' joints in quartz layers, enclosed by mica layers in which there is no evidence of such ruptures, might be cited as cases in point.

(2) BC joints form the second group of tension ruptures in tectonites, but do not occur on a regional scale as do the 'ac' joints. They are found locally as tension cracks in the pebbles in conglomerates or in thin competent beds enclosed by less competent ones and have been investigated mostly by the Wisconsin geologists (L 22). They are here named BC joints since they form parallel to 'b', normal to plaiting surfaces AB, and inclined to shear surfaces 'ab'. They represent, in the same way as do the 'ac' joints, surfaces normal to a strain axis of elongation, in this case A. Since A, moreover, is the chief axis of elongation, the question arises as to why 'ac', and not

BC, tension joints are the chief tension ruptures in tectonites. The answer depends on the same hypothesis as outlined on p. 46 By this hypothesis tension joints probably do form more commonly parallel to BC than parallel to AC but, since the grains, through and between which the ruptures pass, undergo rotation more or less constantly about a common axis 'b', the BC joints tend to be obliterated as fast as they develop. In all probability those which are still visible represent only the very last stage of deformation. 'ac' joints, on the contrary, whatever their age relation with respect to a given deformation, are normal to the axis of rotation (therefore parallel to the direction of movement) and are less disturbed by contemporaneous or subsequent rotation of the grains through and between which they pass. As a result they tend to be developed on a regional scale, whereas BC joints are poorly represented as a rule. Thus 'ac' tension joints localize the <u>effective</u> elongation parallel to 'b'; BC joints localize the usually less effective elongation parallel to A.

Regarding the formation of BC joints, contraction at the close of a deformation may be sufficient to form tension ruptures parallel to the BC plane of strain. More probably, however, they form <u>during</u> the main period of deformation, either with or without the process of "lubrication", as suggested for 'ac' joints.

Indication of tension joints is given in many cases in sections by the so-called "cross" micas, usually biotite. Large, isolated flakes may occur parallel to 'ac' and in such cases have probably crystallized in pre-existing 'ac' tension joints.

Such cases may not easily be distinguishable from a residual orientation (p. 72). If, however, a large concentration of such micas lies normal to 'b', and the flakes are relatively large and undeformed, the probability is that they are localized in this position due to later crystallization in tension joints and do not represent a residual orientation.

Fig. 35 shows a girdle of cross biotite in a tectonite whose maximum, although it has been interpreted differently by Sander, may represent filling of BC tension joints. 'ab' is a visible shear surface and the average cross biotite is represented by BC. The strain axes may then be ABC as shown, with one of the planes of least distortion represented by the shear surface 'ab'. The remainder of the biotite, whose cleavage poles lie in the girdle, may represent a residual orientation. A third possibility which must be considered is that the biotite represents filling of shear joints.

Strength Relations

The investigation of shear surfaces and ruptures in tectonites involves the distinction of two different types of rock failure. Shear surfaces result from the mass effect of partial-movements (p. 32), as originally interpreted. Ruptures result from a type of movement (in contrast to partial-movement) by which the material does not remain a continuous unit. They express qualitatively the elastic limit of the material. Deformation within the elastic limit up to and including failure by fracture falls under static tectonics.

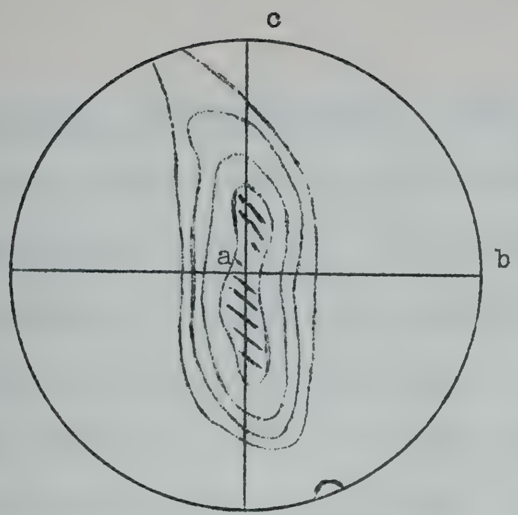


Figure 30 p.81

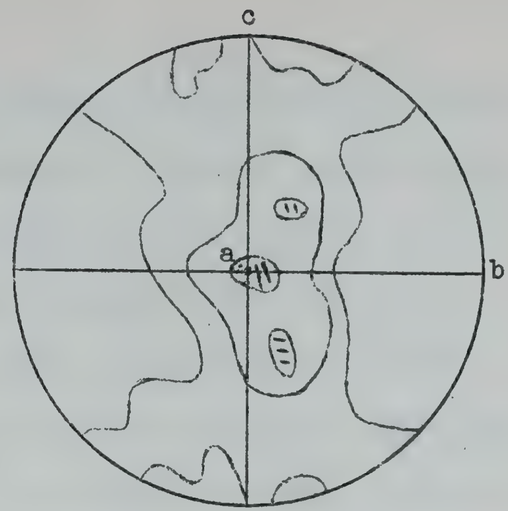


Figure 31 p.81

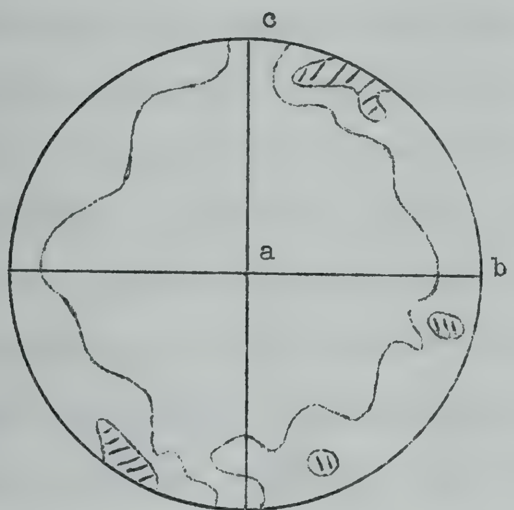


Figure 32 p.81

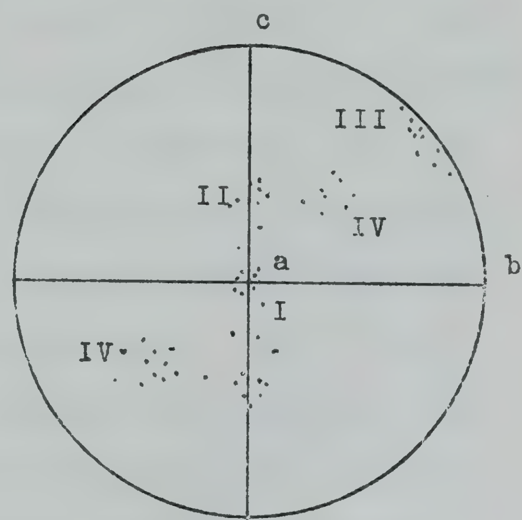


Figure 33 p. 86

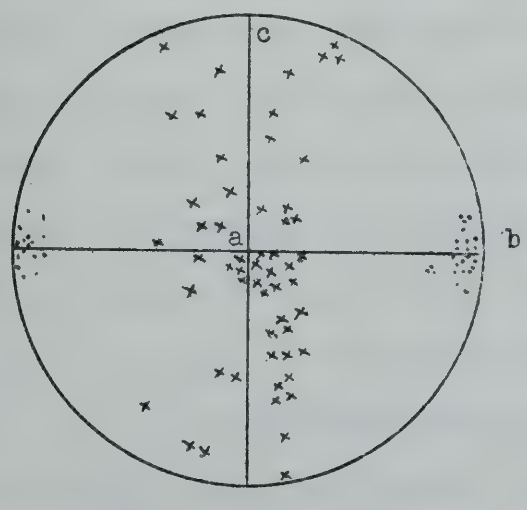


Figure 34 p.90

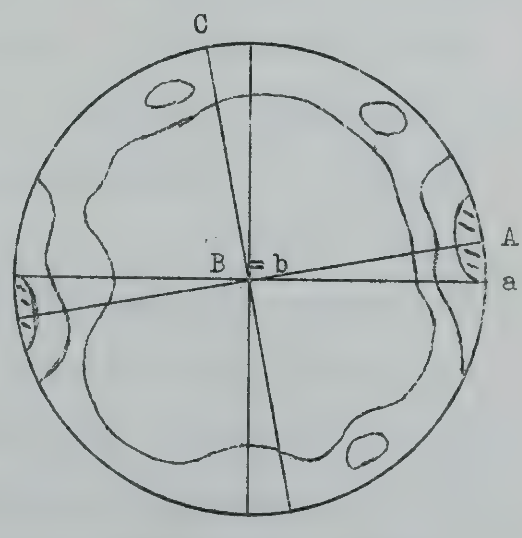


Figure 35 p.94

<u>Ludwig's "Flow" Curves</u> - Fig. 36 of Ludwig's "flow curves" shows in an instructive way the strength behaviour of four crystalline substances A,B,C,D. The arrows indicate the directions of increasing E (modulus of elasticity) and strain. For A,B,C the deformation as far as point S is strictly reversible and within the elastic limit; the flat curves up to this point also indicate that stress is proportional to strain, in accordance with Hooke's Law. Beyond S, the materials behave differently. C is extremely ductile, and beyond the elastic limit S its E decreases. A and B are much less ductile, and the E's of these substances increase, but at rates not directly proportional to the stress, until a maximum is reached. At 'm' they are deformed only elastically; at 'n', partly elastically, but with irreversible deformation, especially in the case of B, rapidly increasing. At 'o' the maximum E for B is reached and its deformation is represented only by flow, however large the stress may become; at 'p' the same is true for A. From this standpoint partial-movement in rocks represents deformation beyond the elastic limit of material which, in general, has limited ductility. "D" illustrates the type of curve which might occur for a tectonite. In general it rises, as do A and B, and indicates an increasing E. Locally, however, it shows dips (decrease in E) on its course to the final maximum. As is usual, the case for any rock system is more complicated than the laboratory results would indicate.

An important case arises if A and B should be deformed in contact with each other. If the stress on elements of A is transmitted to A essentially <u>through</u> elements of B, then 'o'

represents the <u>effective</u> E for A as well as the <u>actual</u> E for B. That is, beyond 'o' A can not be deformed further, since B at this point flows (i.e. its E is stationary) and it is no longer capable of transmitting stress. The curve for A thus ends abruptly at 'o' if <u>no</u> stress is transmitted to it; if a proportion of the stress is transmitted to it, its curve ends at a point between 'o' and 'p'.

<u>Quartz-in-Calcite Tectonite</u> - This condition is commonly realized in rocks, and Figures 37 and 38 show the results of a statistical analysis which indicate it. A calcite tectonite contains isolated heterometric quartz grains whose axes (crystallographic) are shown in Fig. 38. The cleavage poles of the calcite matrix are shown in Fig. 37. The calcite has the typical tectonite orientation - i.e., a girdle normal to 'b'. The quartz shows, however, only remnants of a girdle about 'b' and the majority of the axes lie <u>in</u> 'b'. This is an almost unknown orientation for a tectonite in which quartz forms a major constituent and is explained as follows - Practically none of the stress acting on the rock is transmitted to the isolated quartzes, since the abundant calcite absorbs most of it. Quartz has ordinarily a higher E than calcite and would be represented in Fig. 36 by A; calcite by B. Under the conditions in this tectonite the curve for quartz (A) would end part-way between 'o' and 'p' and the effect of the fraction of the stress transmitted to it is represented by the incomplete, but typical, 'ac' girdle at the margin of Fig. 38. The majority of the heterometric quartzes are subjected only to <u>external rotation</u> (not to deformation)

and, since 'b' is the axis of rotation, they tend to be oriented with their longest <u>dimensional</u> axes parallel to 'b'. The orientation of the <u>crystallographic</u> axes parallel to 'b' is due to a <u>pseudo-lattice</u> orientation, not to a true lattice orientation by deformation of the quartz grains. Since quartz tends to fracture most easily sub-parallel to the vertical or optic axis (as seen from undulose extinction and associated fractures) grains of rod-like shape are locally abundant. Rotation of such quartz embedded in a calcite matrix results in a pseudo-lattice orientation as shown in Fig. 38. This tectonite shows, therefore, true lattice orientation of calcite and of a small proportion of the quartz, and a pseudo-lattice orientation of the remaining quartz. It serves as a practical example of the influence of one type of fabric element upon another under given conditions. If quartz and calcite had similar breaking strengths, the dimensional orientation of the quartz in Fig. 38 would not be found. If the proportion of quartz to calcite had exceeded a certain ratio there would likewise be no dimensional orientation. Similar examples of quartz embedded in mica are known. In statistical analysis, therefore, it is necessary to make allowances for the possible influence of one kind of grain on another which is relatively less abundant, and has markedly different strength properties.

The relation between grain orientation and crushing strength of tectonites has possible applications in quarrying work and one example has been investigated jointly by Sander, Drescher, and Felkel (L 25). A marble was selected which had no visible fabric planes or directions. The first step consisted

in finding the tectonic axis 'b'. Statistical analysis showed the usual girdle of cleavage poles, normal to which 'b' lies. A set of cubes was then sawn for crushing tests and oriented with respect to 'b' as in Fig. 39. The girdle of cleavage poles is shown on the face Z in its true position with respect to the 'b' direction. Its chief maximum indicates an average position of the calcite cleavages sub-normal to X and Y and sub-parallel to Z. Tests on cubes of this orientation show, in summary, the following - The direction of greatest crushing strength is normal to Z, that of least crushing strength is normal to X. Normal to Y (parallel to 'b') the crushing strength is intermediate but closer to the minimum than to the maximum value. These values are in direct correspondence with the grain orientation. Pressure applied normal to 'b' yields the maximum and minimum values; pressure parallel to 'b' yields an intermediate value. Thus, without statistical analysis, it might be possible to determine 'b' in a massive quarry-rock through investigation of crushing strengths of cubes whose orientation to one another was known. The axis of the zone which contains the maximum and minimum crushing strengths would then be 'b'. The relation of 'b' to the joints and ruptures in a quarry would then be determined and in part at least, the structural history worked out.

Folds and Folding

Thus far in the discussion of tectonites we have considered only homogeneous deformation and the production of surfaces which are essentially plane. In a homogeneous deformation straight lines remain straight, planes remain planes etc. This implies two things - (1) The amount of relative movement in adjacent shearing surfaces varies arithmetically (i.e., as a linear function) and (2) The velocity of relative movement is constant in all parts of any one surface. (Cf. Fig. 12.) A deformation of this type can not produce a fold. It can do no more than affect the grain orientation and symmetry of a pre-existing fold. Folds (or any curved surface) form therefore only in structures which have been inhomogeneously deformed, i.e., in structures in which either one, or both, of the above conditions are not fulfilled. Genetically, two types may develop - flexure folds or shear folds. Mixed types, which combine features of both, are common. Descriptively, many other classifications are possible but these, with one exception, are not considered here.

Flexure Folds - If shearing occurs between the members of a series of beds arranged in parallel position so that the velocity of relative movement at different points in any one shear surface is not constant, the surface, unless rupture occurs, becomes curved in order to accommodate itself to this condition. In Fig. 44(a) shearing takes place parallel to AB, originally a plane between two beds, and it is assumed that there is no restriction to movement between them. The curved surface AB is seen to be directly

connected with variations in velocity of relative movement. It increases from zero at C on both sides to higher values at A and B. The shear surface is the fold. This simple case may be expanded to include more complicated natural examples. The size of a flexure fold follows the 'competence' rule. That is, of two layered materials in contact with each other, the more competent will 'flex' into larger folds than the less competent. Drag folds, representing incompetent material, are an expression of this rule. Geometrically, the thickness of any one fold remains constant, although in nature this is seldom exactly realized. Between beds of varying competence, in accordance with the 'competence' rule, flexing causes development of open spaces at the crests and troughs of the folds formed. These openings are commonly filled with heterogeneous material which represents either a para-tectonic or a post-tectonic crystallization. The relation of the grain orientation of such filling material to the grain orientation of the flexure immediately adjacent will indicate which type of crystallization took place. The orientation will be similar for para-tectonic crystallization and will be either different, or lacking altogether, for post-tectonic crystallization.

The relation of grain orientation in flexure folds to the shape of the folds is of practical importance in determining age relations. Flexure folds in limestone, sandstone, etc., insofar as no evidence of grain orientation is obtainable from them, are non-tectonites, and are not considered here. Flexures in layered material already possessing a grain orientation are shown in Fig. 40. Three statistical analyses of quartz from the outer layer were made from sections taken at the points of contact of

the tangents S_1, S_2, S_3 with the flexures. The maxima for the quartz axes are shown for each tangent by dashed lines c'. In each case the angular relation of axes and tangent is approximately the same (20°, 30°, 25°). Since the quartz axes have no symmetrical relation to the axial plane of the fold, it may be concluded that the grain orientation was present before the folding. Further, since there is no parallel alignment of axes in any direction through or across the fold, it may be concluded that there has been no deformation since its formation. Other cases, analysed similarly, may yield information on age relations of considerable value.

Shear Folds - If a series of layered material is mechanically indifferent to a deformation, so that the direction of shearing is inclined to the layers, shear folds are formed. These may be of two kinds, as illustrated in Fig. 41. (a) represents a series of patterns drawn on the edges of a pile of thin cardboard sheets. In (b) the sheets have glided over one another according to the principle of homogeneous deformation. The relative movements, indicated by the arrows, have no symmetrical relation to the attitude of the patterns. Comparison with (a) shows that there has been no distortion of straight lines, and no formation of curves not already existing in (a). The circles of (a) are the ellipses of (b). The shapes of the curves of (a) are changed and distances between pairs of lines have altered (thickening and thinning of beds). Since the deformation is homogeneous and no new folds have formed, the curves of (b) are profiles of pseudo-shear folds. Schmidegg (L 26) has analysed as follows the changes in

symmetry to be found in pseudo-shear folds - If the profiles of the pre-existing folds represent second-order sections (i.e., circular, elliptical, parabolic, or hyperbolic sections), homogeneous deformation, as in (b), produces no change in the symmetry. If the profiles are third- or higher-order sections, the symmetry is retained only if the plane of deformation (parallel to the plane of the drawing in Fig. 41) contains the axes of the folds concerned. Thus in (b), insofar as the patterns (representing fold profiles) are not second-order sections, the symmetry they show in (a) is not retained. These geometrical data may be useful in cases in which homogeneous deformation of a pre-existing fold pattern is suspected.

Inhomogeneous deformation of certain patterns, as in (c), results in curves which represent profiles of true shear folds. In any one shear surface the velocity of relative movement is constant at all points (in contrast with flexure folding); the movement in adjacent surfaces, however, varies as a non-linear function, indicated by the heavy curved line through the centre of the distorted ellipses of (c). In (b) the movement in adjacent surfaces varies as a linear function, indicated by the straight line cutting through the three ellipses. The pairs of straight lines of (a) are curves in (c) and show much thickening and thinning. Pre-existing curves may be either opened or closed by inhomogeneous deformation, depending on their attitude to the shear surfaces and the direction of relative movement. In contrast with flexure folds, the shear surfaces are not the fold.

Application of the geometry of shear folding illustrated by (c) postulates a system of shear surfaces in which the movement,

as represented in adjacent surfaces by the heavy central curve of (c), varies in a rhythmic fashion to form a complete system of folds. This idea has been exploited particularly by Schmidt (I 23) under the term <u>Gleitbretterfalten</u> and considerable inconclusive discussion has arisen as to the abundance of such folds in nature. Without doubt they occur on a small scale, as the following case shows. In Fig. 42 is shown the orientation of the cleavage poles of calcite, measured from the specimen of marble sketched in the centre. Both diagram and sketch have similar orientations and the specimen is about one-half natural size. The folds in the marble are composed of graphitic material and are thickened at the crests. Breaking surfaces of the marble are indicated by the approximate parallel lines cutting through the fold. The orientation of the grains indicates that these breaking surfaces are shear surfaces and therefore loci of movement. The primary structure (graphitic layers) has been mechanically indifferent to the deformation and has attained its present folded condition by shear folding, as in Fig. 41 (c). The fact that the fold in Fig. 42 is symmetrical with respect to these surfaces is not to be mistaken with a plaiting process, or "flow" cleavage of the Wisconsin type (See p. 77)

There are no reliable <u>field</u> criteria for shear folds. In Fig. 44 (b) are shown symmetrical profiles representing them geometrically. There is thickening of crests and thinning of the limbs and no change in degree of curvature. These regular forms are rare in nature, however. The fold in Fig. 40, for example, shows thickening on the crest but the analysis indicates a flexure fold, not a shear fold. The thickening is a result of filling by

para-tectonic crystallization and is not caused by shearing movements accompanying an inhomogeneous deformation, as in Fig. 42. Inhomogeneity in the deformation is probably very widespread but evidence of shear folds developed from it is dependent on an observable primary structure. Lack of certain evidence of shear folds can not be interpreted, therefore, as due to absence of inhomogeneous deformation.

Mixed types, combining features both of flexure and shear folds, are probably of more common occurrence than shear folds alone. They may be recognized in many cases by petrofabric analyses. Fig. 43 shows the orientation of cleavage poles of calcite measured from the centre of the fold shown in the inset. The outer part of the fold is composed of mica which bends around the crest and shows many minor crenulations. Its attitude indicates a flexure fold. The calcite orientation, on the other hand, indicates shear surfaces parallel to the limbs of the fold and cutting through the crest. This implies shear folding and the mica crenulations in the crest of the flexure fold are probably true shear folds. By this means the two processes of folding may be separated and their age relations determined. Practical application of this point may be made in many cases in which field criteria are inconclusive.

Flexure and shear folds may be compared with the concentric and similar folds described in most text-books. Fig. 44 illustrates simple geometrical examples of these. The profile of a concentric fold is shown in (a). The combination of a fixed centre of curvature O and increasing radii 'r' keeps the arcs

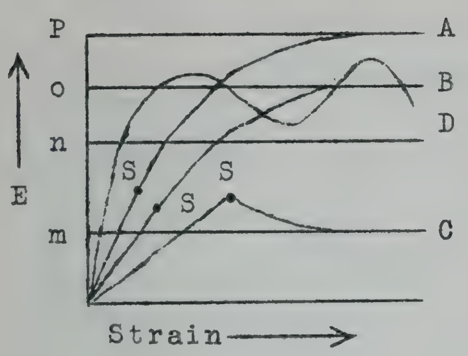


Figure 36 p. 95

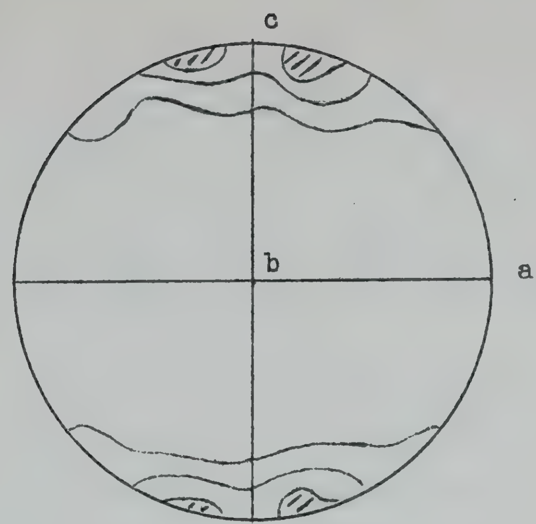


Figure 37 p.96

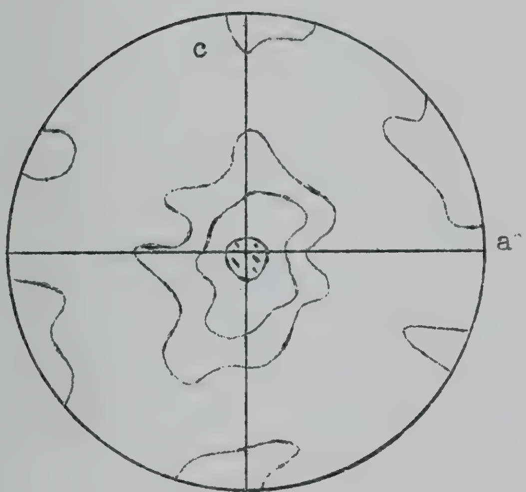


Figure 38 p.96

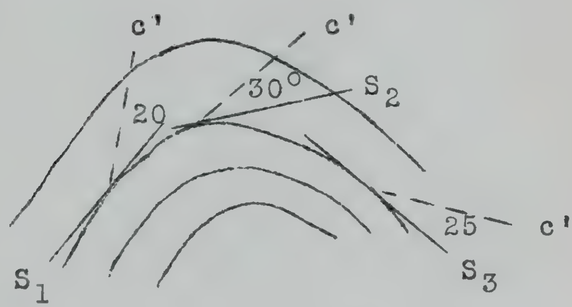


Figure 40 p. 100

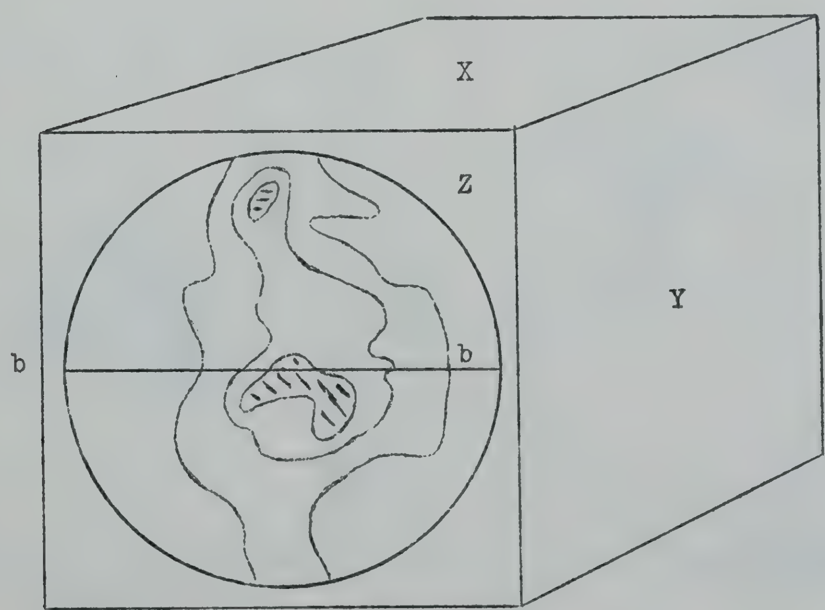


Figure 39 p. 98

Note

See Sandor p.45. (a) in text corresponds to Abb. 21, (b) to Abb. 22, and (c) to Abb. 23.

Figure 41

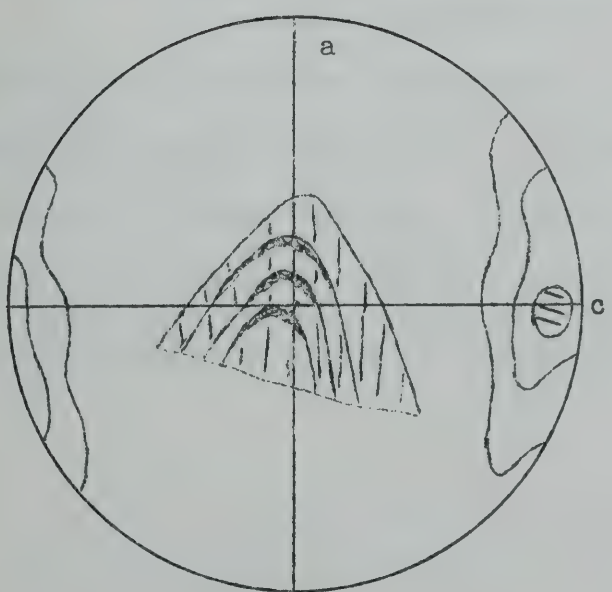


Figure 42 p. 103

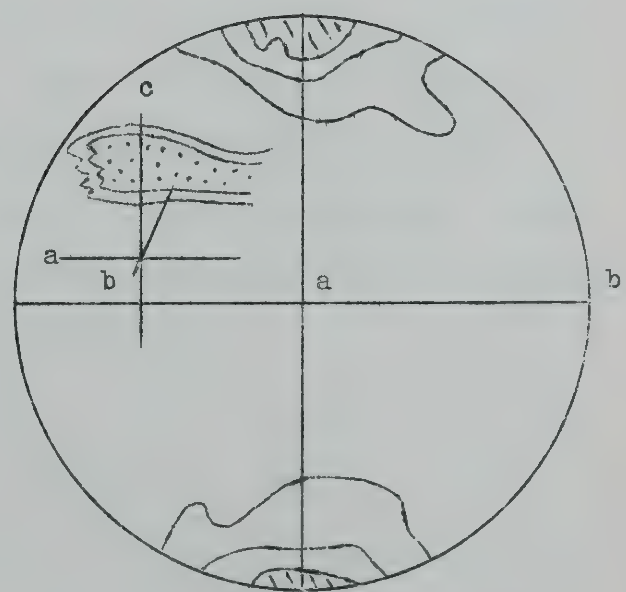


Figure 43 p. 104

fixed distances apart and causes decrease in the degree of curvature from O outward. This corresponds to absence of thickening and thinning, and to "dying out" of concentric folds. The profile of a similar fold is shown in (b). The combination of variable centres of curvature (O^1, O^2, O^3, O^4) and a fixed radius makes the degree of curvature constant and allows the arcs to approach each other on the right and left. This corresponds to thickening of crests and troughs, thinning of limbs, and lack of the "dying out" effect of concentric folds. The profile of a mixed type is shown in (c). The combination of variable centres of curvature (O^1, O^2, O^3, O^4) and increasing radii (r^1, r^2, r^3, r^4) causes decrease in the degree of curvature and allows the arcs to approach each other on the right and left. Since the former is characteristic of concentric folds and the latter of similar folds, it is apparent that many folds do not fall into either the 'concentric' or 'similar' class. (Cf. Fig. 43)

As regards nomenclature, the term 'concentric' includes, from the descriptive standpoint, all that is meant by 'flexure' and is a useful field term. The same holds for 'similar' and 'shear'. Since, however, 'flexure' and 'shear' are genetic terms, it is obvious that they are more useful in all cases in which folds are analysed in terms of the grain orientation.

Schistosity Hypotheses

Until modern petrofabric analysis was commenced, all evidence of deformation in rocks was obtained from structures and textures visible in the field or under the microscipe. Most observations of these structures and textures relate to the schistosity, cleavage, or foliation. For almost a century various investigators have concerned themselves with the origin of schistosity, and in many cases have carried out ingenious experiments in the attempt to support their hypotheses. These early conceptions form an instructive background to present-day ideas and are summarized here for purposes of comparison.

In 1843 Phillips wrote of a "creeping movement among the particles of the rock, the effect of which was to roll them forward in a direction always uniform over the same tract of country". Without being particularly definite, Phillips foreshadowed under "creeping", better than any of his successors, Sander's idea of partial-movement and a tectonic axis. Following Phillips, Sharpe postulated in 1849 that flattening of particles normal to the pressure resulted in schistosity. Sorby (1853), as the pioneer microscopist, found that mica was arranged parallel to schistosity and believed it to be normal to the pressure. Laugel (1858) postulated non-rotational strain as an essential in development of rock cleavage. Tyndall (1859) and Daubrée (1879), the classic experimenters of the last century, believed that schistosity developed normal to the pressure and that a dimensional orientation of the particles was unessential.

We come now to more modern times. In 1893 Becker's paper (L 27) on the mathematical treatment of homogeneous strain appeared. His treatment of the strain ellipsoid forms the basis of the hypothesis of grain orientation developed on p.42 to explain shearing phenomena in rocks. In accordance with the views of Tyndall and Daubrée, he believed that a dimensional orientation of grains was not essential for the production of schistosity. He believed further that all schistosity could be represented in a strain ellipsoid by planes of least distortion. Opposed to his views were those of Van Hise and Leith who believed, as a result of their extensive field and microscopic studies in the Lake Superior region, that schistosity was due to "arrangement of mineral particles with their longer diameters, or readiest cleavage, or both, in a common direction." (L 28) In the language of petrofabric analysis, they emphasized dimensional orientation. With regard to the possibility of lattice orientation, Leith wrote at that time (L 1) - "The crystallographic or vector properties of the particles of any mineral are parallel only when they have uniform relations with the parallel dimensional axes." This parallel arrangement is brought about in three ways, which, in order of decreasing importance, are as follows -

1. By recrystallization, in parallel position, of new minerals.
2. By rotation of particles.
3. By gliding along crystallographic planes. This evidence would be destroyed by recrystallization.

As described by Van Hise and Leith, these three processes correspond to -

1. Development of a growth fabric after the Wegsamkeit (path of least resistance) in the parallel surfaces.
2. External rotation.
3. Lattice orientation.

The plane in which the schistosity ("flow" cleavage) develops is the AB plane of the strain ellipsoid. This plane, however, does not necessarily lie normal to the greatest pressure, as most earlier investigators believed.

The Wisconsin school emphasizes, therefore, a schistosity represented most probably by plaiting surfaces (p. 77), in which a pseudo-dimensional orientation of the grains is brought about, and is followed by recrystallization. Similarly, Becker's analysis emphasizes schistosity as representing shear surfaces, in which neither dimensional orientation nor recrystallization is essential. For more than thirty years these apparently incompatible hypotheses have faced each other in America, without prospect of solution. In Europe Becke's (L 29) "Kristallisationsschieferung" hypothesis supported in large part the Wisconsin ideas.

With existing methods of attack it was apparent that no great advance was possible. The recent combination, however, of fabric analysis with ordinary field and microscopic work, as outlined here, has opened anew the problem of rock deformation. Sander has added external rotation to Becker's interpretation of strain (internal rotation). The lattice orientation of minerals is now an established fact, in addition to the well known dimensional orientation. Foliation surfaces are not all shear surfaces, as Becker believed. His mathematical treatment of strain is sound and his paper in that respect is a classic of its kind; his applic-

ation of his results, however, was too limited, although notable for the period in which he worked.

The Wisconsin analysis of strain includes those foliation surfaces which can be shown to be due to a "plaiting" process and which are formed by a pseudo-dimensional orientation. The recrystallization emphasized by Van Hise and Leith is largely a post-tectonic crystallization, imposed on grains already possessing a lattice orientation. Universal stage analysis will furnish evidence of this lattice orientation for most of the common minerals. If, however, the recrystallization forms a true <u>growth</u> fabric throughout, there will be no evidence of lattice orientation and the original nature of the surfaces can not be exactly determined as due either to shearing or plaiting.

The relation of bedding to cleavage plays an important role. The Wisconsin hypothesis - that foliation is formed parallel to AB of the strain ellipsoid - finds support in that type which lies parallel to the axial planes of a system of symmetrical folds. The field criteria worked out on this basis have proved their usefulness repeatedly and should be better known. A preliminary investigation by the writer (L 24) of this "axial plane" foliation by petrofabric analysis tends to support the Wisconsin interpretation. On the other hand, other types of foliation may develop <u>parallel</u> to bedding, or <u>asymmetrically</u> with respect to it and, if studied by statistical methods, will probably be interpreted as shear surfaces. The "cleavage problem" will therefore disappear as soon as it is realized that there is more than one interpretation possible for foliation surfaces.

This historical sketch of cleavage relations forms an intimate part of the development of petrofabric analysis but must not be thought of as representing the whole field of rock deformation. Foliation surfaces form only part of the megascopic fabric of a rock and are important only in their relation to the whole. The symmetry relations of the entire grain fabric, foliation fabric, and joint fabric of a rock, as outlined in the preceding pages, give the only possible approach to a complete picture of a deformation. Foliation surfaces are only one expression of strain in rocks; much of the strain expressed in the grain orientation does not form part of the megascopic fabric and can only be evaluated after a statistical analysis has been made.

Igneous Tectonites

Igneous tectonites include those rocks which have crystallized from a magma and which now show evidence of partial-movement in their fabrics. Strictly speaking, they do not require separation from the ordinary tectonite type already described; since, however, the megascopic evidence of deformation may be entirely lacking, it is advisable for the present to single them out for special discussion.

Although relatively few petrofabric studies of igneous rocks have as yet been made, all the evidence indicates that deformation (not necessarily megascopic) of varying degree is very widespread and that the orientations of the grain and joint fabrics are entirely similar to those found in tectonites which have never been molten masses. Fig. 45 is from a typical example studied

by Sander. It shows the orientation of the axes of the quartz phenocrysts in a porphyry, the diagram being oriented normal to the <u>linear</u> texture of the unequidimensional grains. The quartz axes lie in a girdle normal to this axis, indicating that it is a tectonic axis (b) in the same sense as for the ordinary type of tectonite. An example studied by Johs (L 30) is also important. A quartz porphyry is in contact with a mica schist. Each has a linear texture and these are in parallel position in both rocks. The direction shown by the quartz phenocrysts and groundmass of the porphyry is ordinarily interpreted as due to an original direction of flow parallel to the enclosing wall rock. Since the phenocrysts show, exactly as in Fig. 45, orientation of the axes in a girdle normal to the "flow" structure, it is evident that deformation has also played a part. The "flow" direction is also a tectonic axis, with rotation and translation of varying amount occurring <u>normal</u> to it. Study of the grain orientation of the enclosing mica schist reveals a deformation-picture in parallel position with that for the porphyry, thus substantiating the conclusion reached independently regarding the porphyry. A further point of similarity with ordinary tectonites is the presence of a regular system of joints sub-normal to the "flow" structure. These correspond with the characteristic 'ac' tension joints described on p. 89 and have in all probability a similar origin.

A granite studied by Maroschek (L 31) also shows quartz girdles, as in Fig. 45. The granite is in large part massive and shows no "flow" direction. The quartz is nevertheless oriented, indicating that partial-movement, at least of small magnitude, has taken place. The girdle in which the quartz axes lie is

parallel to the major joint system, These are 'ac' tension joints, as pointed out in the previous example.

The evidence of deformation in supposedly undeformed igneous rocks is obtainable only by determination of the lattice orientation of the minerals. Knowledge of the dimensional orientation alone is insufficient, since this orientation in many minerals depends in part on the relative perfection of their cleavages. In the case of "flow" structure, therefore, the dimensional orientation may be due either to actual flow (early crystallized, unequidimensional grains suspended in parallel arrangement in a current) or to deformation (interstitial non-crystallized material of sufficient viscosity to transmit stress), or to both (flow accompanied or followed by deformation). The combination of field evidence and data on relations of lattice and dimensional orientation may make possible the distinction of the above cases. In the case of massive igneous bodies, "flow" structure is absent and there is possible only the correlation of the joint fabric with the lattice orientation.

The existence of lattice orientation (and accompanying dimensional orientation) in apparently undeformed igneous rocks does not necessarily imply a great degree of actual movement. In a massive igneous rock, for example, the field evidence would decidely negate a conclusion of this kind. The lattice orientation indicates simply the existence of strain of small magnitude, and, equally as important, it indicates the orientation of the tectonic axis 'b' and plane of deformation 'ac'.

Modern study of fractional crystallization of magmas is incomplete without a petrofabric analysis to evaluate the

relative importance of <u>deposition</u> and <u>deformation</u>. Special features of deposition are discussed on p. 115. The relation of deformation (involving strains of small amount) to crystallization has been little studied, but insofar as present investigations go, the deformation is entirely analogous to that found in other, more highly deformed rocks. The following questions naturally arise - Can deformation be present at an early stage of fractional crystallization due to the fact that a viscous magma behaves partly as a solid? If so, is it comparable in magnitude to that produced at a later stage in which crystallization is largely complete? It is possible at present to investigate these purely mechanical problems by petrofabric analysis and to attempt a correlation of the data with the usual chemical and mineralogical studies.

In recent years detailed field studies of igneous bodies have been made by Hans Cloos and his co-workers in Europe and America. The relations of the joint fabric to the "flow" structure have been thoroughly established and important deductions have been made as to the mode of emplacement and direction of flow of magmas. The Q-joints of Cloos are cross joints and correspond to the 'ac' joint of petrofabric analysis. Linear structures are interpreted, however, only in terms of <u>primary flow</u> and, in many cases, rightly so. The evidence of accompanying, or later deformation cannot, however, be neglected and, as we have seen throughout these notes, it may be in many cases present without being visible. A complete analysis, therefore, must include a petrofabric study, if only to determine that no strain is present in the rock. If present, two points arise - its age relation to

the primary flow and its symmetry relation to the "flow" structure. It may not be possible in all cases to determine the exact age relation ; it is possible, however, to determine the symmetry relation (of the tectonic axis 'b' and the deformation plane 'ac') to the "flow" structure. In the known cases the tectonic axis is parallel to the "flow" structure and the deformation plane is consequently normal to it. Partial-movement, according to tectonite interpretation, (see p. 43) takes place parallel to a direction in the deformation plane, or <u>normal</u> to the "flow" direction of igneous tectonites. These hypotheses are incompatible with each other unless we assume that stresses were transmitted in such a way that the material behaved initially as a liquid and later as a solid. In such case the coincidence of the tectonic axis and "flow" structure is probably to be expected if a strain is superimposed on an igneous body which, due to an earlier-formed "flow" structure, is anisotropic with respect to its strength properties. Cases in which strain is developed <u>during</u> flow of a viscous mass present a more complicated problem, for which criteria are not at present available. Such problems in igneous rocks require, in the same way as for non-igneous types, careful field investigation and statistical analysis both of the lattice and dimensional orientations of the grains.

APPOSITION FABRICS

Apposition fabrics, as explained in the general introduction (p. 5) comprise all fabrics which have not been affected by external stresses. Partial-movement has not taken place in or between the grains and the grain orientation, if any is developed, is a dimensional one, with or without lattice orientation. Gravity plays an important role in the formation of one class - the depositional fabrics - and both sedimentary and igneous rocks furnish examples. Crystallization by growth of grains is important in a second class - the growth fabrics - which have been already mentioned in connection with tectonites.

Depositional Fabrics

Sedimentary rocks - Depositional fabrics in sediments may be formed by deposition from either flowing or non-flowing media. The former resemble tectonites in that they possess a monoclinic symmetry of the megascopic fabric. For example, a ripple-marked sandstone possesses a symmetry plane normal to the axes of the ripples. These axes are rotation axes and the direction of transport of the sand grains lies in the symmetry plane. This plane in tectonites is a deformation plane as well. The similarity between the symmetry of the two fabrics is striking and lends weight to the reality of the hypothesis already outlined for tectonic flow.

Sediments deposited from a non-flowing medium exhibit spheroidal symmetry. There is no flow direction and therefore no

one symmetry plane is diagnostic. $CaCO_3$ deposited in quiet waters forms a rock (limestone) whose fabric shows this symmetry.

Wind-laid deposits will commonly be monoclinic; water-laid, as just noted, will commonly be either spheroidal or monoclinic. Grain orientation of these rocks is little known, but where it is developed it will be entirely dimensional and parallel to the bedding structure. Many minerals, particularly quartz, will have no orientation, so that evidence of symmetry is obtainable only from the magascopic fabric. The study of diagenesis in its relation to grain orientation offers a large field of research.

Igneous rocks - Fractional crystallization in igneous rocks may combine the whole field of petrofabric analysis - i.e., primary crystallization and growth (growth fabric); gravity separation (depositional fabric); and later partial-movement (deformation fabric). As already noted (p. 110) igneous rock studies require petrofabric analysis in addition to chemical and mineral analyses. Since data on the depositional phase of fractional crystallization concern only dimensional orientation, considerable evidence of this kind may be obtained by field observation.

Growth Fabrics

Growth fabrics result from an active orientation process - i.e., one in which the orientation is brought about by the crystallizing forces of individual grains. The type of orientation may be controlled by various factors, but actual transport of material in the solid state plays no part in the process. This is the fundamental distinction from the passive orientation process of tectonites, in which partial-movement takes place. Growth fabrics may

be divided into at least four groups, according to their occurrence - (1) Growth from blastetrices, (2) Wegsamkeit growth, (3) Intergrowths, (4) Isolated crystal growth.

Growth from blastetrices - This type of growth fabric includes all growth of crystal aggregates which, in its initial stages, commenced on a curved or plane surface. A common characteristic of the fabric is the dimensional orientation of the grains with their longest axes approximately normal to the growth surface. The accuracy of this orientation is usually high in filled fractures and cavities, but may be lacking altogether in replacement fabrics. The lattice orientation depends on the type of blastetrix. A blastetrix is said to be isotropic if it exerts no influence on the lattice orientation; it is anisotropic if it influences the orientation process.

Lattice orientation rules known for isotropic blastetrices are - Quartz - vertical axis parallel or normal to the wall. - Calcite - vertical axis parallel or normal to the wall. Dimensional orientation of the type noted above always accompanies the lattice orientations to some degree. This type of growth fabric forms the common cavity and fracture fillings in which parallel growths of crystals occur normal to the walls. Petrofabric analysis brings out features of interest concerning the lattice orientation. One of these is illustrated for calcite in Fig. 46 a,b,c. The growth wall W runs EW in each diagram and the dimensional orientation of the grains is NS (parallel to D). a,b,c represent measurements of vertical axes taken at increasing distances from the blastetrix. The rule for all three is - c' parallel to W, but the accuracy of the orientation according to

this rule increases with increasing distance from W. The black-filled contour intervals in each diagram represent similar percentages, and thus emphasize the relative degrees of accuracy. This example, investigated by Schmidegg (L 32), illustrates the "crowding" effect of innumerable seed crystals forming on a wall. Those which form initially with their vertical axes most closely parallel to the wall (the orientation rule in this example) have preferment; and such grains grow at the expense of others less favourably situated. Due to this sorting effect, the accuracy of the orientation increases with increased distance from the wall, as shown in Fig. 46.

In contrast to isotropic blastetrices, the anisotropic ones control to some extent at least the lattice orientation of the subsequent growth fabric. This is illustrated commonly by replacement of one mineral by another which has essentially the same lattice structure. Clar (L 33) has investigated carbonate replacement by means of petrofabric analyses. In one example of siderite replacing calcite, the calcite fabric shows typical tectonite orientation, although the rock appears megascopically perfectly massive. Measurement of the siderite at the replacement contact gives a diagram in which some grains are oriented with their axes normal to the contact (illustrating growth); the orientation of others corresponds to the tectonite orientation of the calcite. Since the evidence is strong that the siderite is all secondary, it is seen that the calcite wall has influenced the subsequent growth and is therefore an anisotropic blastetrix. Replacement occurs partially by siderite growth conforming to the orientation of the individual calcite lattices, partially by

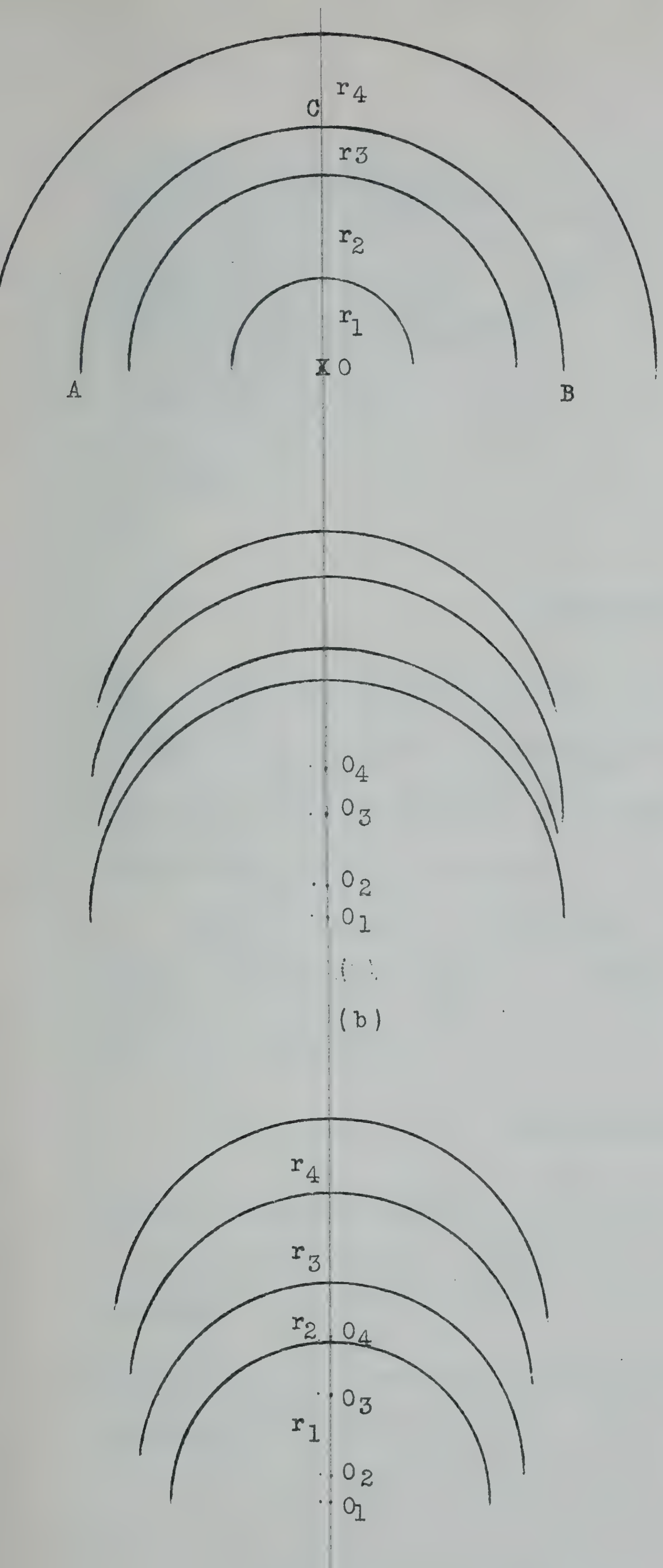


Figure 44 p. 104

Figure 45 p. 110

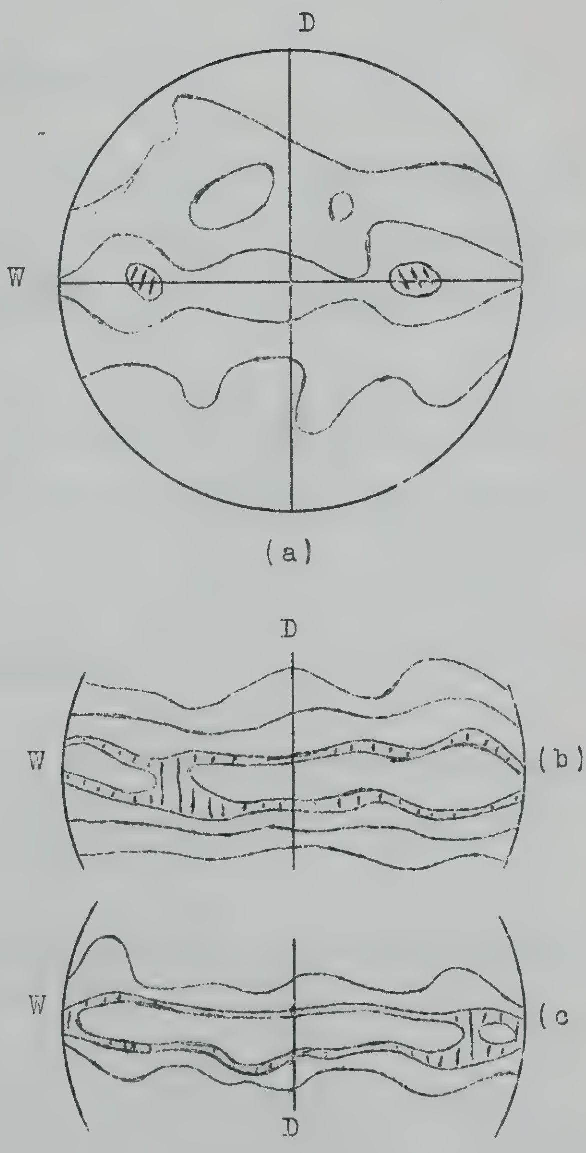


Figure 46 p. 117

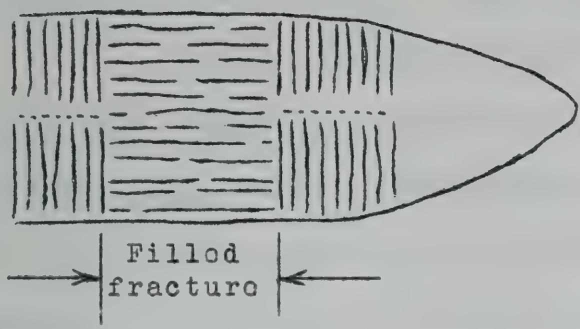


Figure 47 p. 119

Acknowledgment

Figures 13, 18 to 39 inclusive, 42, 43, 45, 46 are sketched from originals in Sander's "Gefügekunde der Gesteine" (publisher Julius Springer, Vienna) and are not reproductions. Much detail in the contouring has been omitted.

Acknowledgment is also made to Doris Korn for Figure 4 and to Walter Schmidt for Figure 6. Figure 47 is sketched from an original by Josef Ladurner.

Notes to Figures

Figure 8 - Constructed to illustrate relation of a shear surface to fabric and strain axes. Not to be confused with a plaiting surface.

Figures 14-16 - Sketched from actual photographs to show principal features.

independent growth with c' normal to the wall.

A second example concerns two generations of magnesite - one having tectonite orientation throughout, and another occurring as lenticular, coarse, white bands in the gray tectonite material. The latter shows tectonite orientation at contacts with the gray magnesite, and growth orientation in the centre of the bands. From consideration of all evidence, the main mass of magnesite is believed to have replaced a calcite tectonite and to have inherited its orientation. The white bands in it are interpreted as the filling of later fractures. At the walls the second generation magnesite inherited the tectonite orientation, but further out in the fracture was able to break free of this control and to follow a growth rule.

Another phase of this "Baugrund" or inherited orientation is shown in an example of a "stretched" belemnite investigated by Ladurner. (L 34) Undeformed parts of the fossil structure are filled with quartz grains which have grown inward from the wall to form in a radial texture. (Fig. 47). The vertical axes of the grains are parallel to the dimensional axes. In adjacent, deformed parts of the fossil are quartz-filled fractures in which the grains have grown normal to the <u>fracture</u> wall, as shown in the figure. The vertical axes, however, remain essentially normal to the <u>external</u> walls of the belemnite, as in the undeformed parts of the structure. This again is an inherited lattice orientation, but does not involve replacement as in the first cases considered.

Further investigation of fabrics developed by growth from blastetrices will bring out additional details of practical importance in determining age relations, since up to the present

very little work on these rock types has been carried out.

The second type of growth fabric (Wegsamkeit) includes grains which follow paths of least resistance but do not crystallize in open or opening fractures. Common examples of this group are growths of mica, hornblende, etc., in cleavage surfaces. They have a dimensional orientation with respect to these surfaces but do not possess a lattice orientation. They must be carefully distinguished from the products of post-tectonic crystallization (recrystallization of material previously deformed, usually with preservation of the lattice orientation). Porphyroblasts belong partly in this Wegsamkeit group and partly in the preceding one, depending on the circumstances of their growth. Their orientation has already been briefly discussed (p. 53).

The third type of growth fabric includes what are commonly known as intergrowths, of which myrmekite, graphic granite, and perthite are the best known examples. Preliminary studies have been made of the quartz of the first two (L 35), with results indicating that no one orientation rule holds for all cases. Further investigation is necessary.

The fourth type of growth fabric includes isolated crystal growth in a magma, as shown by phenocrysts. A dimensional orientation may arise if the phenocryst is heterometric, and there is flowage during crystallization. This would correspond to a true "flow" structure (p.110).

APPLICATIONS

Study of the foregoing pages will have already suggested to the reader many possibilities of practical application of petrofabric analysis. A few of these have been specifically pointed out. As with all new methods of investigation, there must be a testing period during which data are collected and a rational interpretation is evolved in terms of other proven methods. Practical application is then possible. Petrofabric analysis has reached the application stage in many of its phases and has been successfully used already in a number of field problems.

Field Mapping - The study of grain orientation has been instrumental in emphasizing, as never before, the necessity for more detailed field mapping of directions (linear textures and structures) and surfaces (parallel, plane, and near-plane structures) in deformed rocks. Investigation of directions has been confined until the present, almost entirely to observation of the strike and pitch of fold axes. Mapping of surfaces in deformed rocks, such as joint systems, is carried out only locally in mines and seldom on a regional scale.

Careful examination of outcrops of schists, gneisses, marbles, etc., in which no evidence of folding is seen, will reveal in most cases a linear texture or structure. If the rock has a well developed schistosity, the direction is seen in the schistosity surfaces. If schistosity is lacking, there is usually evidence of a "pencil" structure. These directions may be recognized by parallel arrangement of elongated grains (mica flakes, quartz, etc.), or by minute parallel crumples. The preceding

discussion of tectonites shows that these linear textures have the same tectonic significance as the axes of folds. Movement takes place normal to them, as with fold axes, and one obtains thereby a picture of the movement not thought possible formerly. Since large areas of highly deformed rocks are known in which folds are practically absent (as far as field observation goes), the importance of these <u>tectonic axes</u> is obvious. Their strike and pitch should be scrupulously mapped for future, if not immediate, use. Even if no further analysis with the Universal stage is contemplated, the accumulation of these data concerning tectonic axes is an important preliminary step in unravelling the structure of a region.

Mapping of the position of bedding and foliation planes is at present carried out in most field work. Joint systems, on the contrary, are seldom mapped, except in igneous masses and sedimentary formations. This neglect has arisen because of the prevalent belief that joint systems in deformed rocks have little or no connection, genetically, with the main deformation producing rock flowage. It is true that there need not necessarily be <u>contemporaneity of development</u> of schistosity and joints; on the other hand, investigation of grain orientation tends to show in most cases a <u>symmetry relation</u> between failure by fracture (joint systems) and failure by flow (schistosity etc.). That is, the deformation axes postulated for development of foliation tend to have the same orientation for development of joint systems, without regard to age relations.

The 'ac' joints discussed on p. 89 have particular importance in field mapping. They lie normal or sub-normal to the

tectonic axes (or fold axes) and are due to tension. They are very widespread and are usually easily identified. Their persistent orientation approximately normal to the tectonic axes is a particularly valuable criterion in localities in which accurate measurement of the linear texture is difficult to carry out. Mapping of these joints thus acts as a check on the observed position of the tectonic axis.

These facts concerning tectonic axes and joint systems have already been successfully applied in a number of field areas investigated. In south-western Germany a number of small areas have been subjected to petrofabric analysis, mostly by students of Rüger,then at Heidelberg, (L 36) and several controversial problems have been settled. These concerned the conception that formations of differing lithology and texture had undergone radically differing deformations and were structurally unrelated. Study of the grain and joint fabrics, however, shows similar features of deformation, and indicates the fallibility of sole reliance on the megascopic fabric in interpreting a structure. Investigations of a similar nature are being carried out in the Bavarian Forest and Danube valley regions. (L 36)

In the Eastern Alps Schmidegg (L 36) has already obtained sufficient petrofabric data to indicate that the "overthrust-sheet" (Decken, nappes etc.) theory of the Western Alps is not applicable in the large area covered by his field work. Steeply inclined, in many cases vertical, tectonic and fold axes are characteristic over many miles of territory, indicating a structural history quite different from that postulated by "nappe" tectonics.

In Lapland Sahlstein (L 36) has done preliminary work over a large area, with results so far which indicate the absolute necessity of petrofabric analysis in interpretation of the structure.

In America no published information on field areas is yet available, as far as the writer is aware. In the Canadian pre-Cambrian, and in the Appalachian regions, field problems are being studied by a number of petrofabric investigators.

Special Problems - In conection with areal mapping a number of problems may arise which deserve special mention. They concern age relations for the most part and will be discussed briefly.

(1) In cases in which the field data are too meagre, or appear conflicting, the determination of conformability or unconformability of adjacent formations may be made by petrofabric analysis. Conformable formations should show similar grain orientation; unconformable formations should show certain dissimilarities. Later deformation may of course affect both, but usually traces of earlier deformations can be found from the grain orientation and thus give the criteria required.

(2) The study of shear and fault zones with the aid of petrofabric analysis will give more exact information than is obtainable from field observation alone. Determination of direction of movement, direction of grain elongation, etc,. are essential to such investigations and in areas of economic interest have particular importance in their relation to distribution of ores. Both optic and X-ray methods are applicable to such problems.

(3) Study of veins is seldom complete if based only on field and ordinary microscopic data. Petrofabric analysis should prove an exceptionally useful tool in attacking the many questions which arise in relation to the physical conditions existing during or after emplacement of veins. Insofar as veins of these types carry valuable metals, the problems become problems of ore genesis, the solution of which may be of economic value.

Few studies of this type have been made, but the possibilities of positive results are considerable. One example from Sweden investigated by Korn (L 10) shows that the rock enclosing a chalcopyrite-fluorite vein has undergone two deformations. The vein material, on the other hand, shows evidence of only the later of the two. Deductions of this kind are obviously of value in economic problems.

Preliminary work on growth fabrics which occur as replacements indicates the importance of this field of investigation. For example, in many places quartz veins have highly sinuous forms and drag fold shapes. Many of these have undoubtedly followed and replaced drag fold structures; in other cases they may themselves have been folded. Replacement processes are known, however, in certain cases to preserve in newly-formed material, the orientation of the replaced material. If the latter, for example, has a tectonite orientation, literal interpretation of this <u>inherited</u> orientation (p. 119) may lead to incorrect conclusions regarding evidence of deformation etc., if sufficient accessory evidence is not brought to bear on the problem.

(4) In the quarrying of material such as slate, marble, and granite, knowledge of grain orientation, and of the generalizations

which it is possible to make as a result of such analysis, may be of practical importance. X-ray analysis of slate, and optic investigation of marble and granite with the Universal stage will locate the tectonic axes of these rocks if megascopic evidence is lacking. The relation of crushing strengths to the position of the tectonic axes (p. 97) has been determined for marble and may have similar relations for other quarry materials. Since knowledge of crushing strength in its relation to directions and surfaces is in many cases of importance, it is seen that a technique may be worked out with this application as a goal.

In the case of slates an X-ray technique may be developed for texture classification as well as for grain orientation, and thus supplement mechanical tests. In granites knowledge of the role that quartz with strong "undulatory" extinction plays in grain orientation may save time and expense in exploration work for building stone. In massive marbles determination of the degree of development of tectonic axes and of non-megascopic shear surfaces may be valuable in classifying the stone for building or monumental work.

The above résumé of known and possible applications serves only as a frame into which various problems may be fitted as the occasion arises. Other applications will undoubtedly come into use as our data, and confidence in them, increase.

APPENDICES

Nomenclature

The following alphabetical list is intended as an aid to those unfamiliar with the German nomenclature. Only those terms which have not been used in the preceding text are defined here; all others are provided only with page references. In the preparation of this section the writer is particularly indebted to Doctors Schmidegg and Felkel of Innsbruck for their criticism and assistance.

a-Gefüge - See Längsfäden.

Abbildungskristallisation - ("portrait" crystallization) - p. 50.

ac-Reissklüfte - ('ac' tension joints) - p. 89.

Achenlinien - (axial lines) - p. 60.

affine Deformation - (homogeneous deformation) p. 40.

aktive Regelung - (active orientation process) p. 6.

andersphasige Kristallisation - Same as Umkristallisation.

Anlagerungsgefüge - (apposition fabric) pp. 6, 115.

atomdynamisches Gefüge - All features of a fabric resulting from molecular action (as distinct from mechanical action).

Aufbereitungsregelung - ("sorting" orientation process) - An orientation process acting on the particles of sediments during their deposition. It is strictly a dimensional orientation and is independent of the size or specific gravity of the particles.

<u>b- Gefüge</u> - ('b' fabric). See Querfaden.

<u>Beanspruchung</u> - Any external force which acts on a body.

<u>belteropores Gefüge</u> - (belteropore fabric) - A fabric in which the best Wegsamkeit (path of least resistance) to passage of solutions has been utilized.

<u>Bereich</u> -Comprises any area <u>or</u> volume of material of which a study is being made.

<u>Bewegungsbild</u> - (movement-picture)

<u>Biegefalte</u> - (flexure fold) p. 99.

<u>Biegegleitung</u> - (bend-gliding) p. 99.

<u>Blockierungsporen</u> - Pores or fine canals occurring along the intersection lines of cleavage surfaces of single grains or aggregates of grains.

<u>Boehmsche Streifung</u> - (Boehm's lamellae) p. 36.

<u>Deformationsebene</u> - (deformation plane) p. 41.

<u>Deformationsgefüge</u> - (deformation fabric) pp. 6, 32.

<u>Durchbewegung</u> - (penetrative movement)

<u>Durchregelung</u> - (essentially the same as Regelung)

<u>ebene Deformation</u> - (plane deformation) p. 41.

<u>ebenes Parallelgefüge</u> - (plane-parallel fabric) - A parallel fabric with a predominant s-surface.

<u>einphasige B-Tektonit</u> - (single-phase B-tectonite) - A B-tectonite formed by a single uninterrupted deformation.

<u>Einregelung</u> - (essentially the same as Regelung)

einscharige Scherung - ("single-set" shearing) A plane deformation in which only one set of shear surfaces is well developed.

Fadenporen - Blockierungsporen of calcite. Probably formed by deformation of the grains.

Flächenbüschel - ("surface-cluster") - Any group of s-surfaces in a tectonite which have a common line of intersection.

Formregelung - (dimensional orientation process) p. 7.

Gefüge - (fabric) p. 4.

Gefügeachsen - (fabric axes) p. 32.

Gefügeanalyse, Gefügekunde - (fabric analysis) p. 4.

Gefügeelement - (fabric element) p. 6.

Gefügekunde der Gesteine - (petrofabric analysis) p. 4.

Gefügesymmetrieebenen - (fabric symmetry planes) p. 33.

Gefügetracht - ("fabric habit") - A statistically recognizable relation between the dimensional and crystallographic axes in the grains of a fabric.

gepresstes Starrgefüge - A fabric in which favourably situated elements show translations (by gliding) without rotation and in which unfavourably situated elements are unchanged

geradebahnige Gleitung - ("straight-path" gliding) - The type of gliding which forms shear folds. p. 101.

<u>gleichphasige Kristallisation</u> - ("same-phase" recrystallization) -A recrystallization as a result of which no new mineral species appear.

<u>gleichscharige Scherung</u> - (or Gleitung) - A "zweischarige Scherung" in which the two directions of shearing are equally developed.

<u>Gleitbrett</u> - ("glide-board") Material undergoing a form of "geradebahnige Gleitung" (which see)

<u>Gleitbrettfalten</u> - ("glide-board" folds) p. 103.

<u>Gleitfläche</u> - (glide surface) p. 40.

<u>Gleitgerade, Gleitrichtung</u> - (glide line, direction) p. 40.

<u>Gleitplatten</u> - The elements of a "Gleitbrett".

<u>Gürteldiagramm</u> - (girdle diagram) p. 39.

<u>Gürtelklüfte</u> - Same as ac-Reissklüfte.

<u>Harnisch</u> - A shear surface of a shear zone tectonite. p. 67.

<u>heteroachse Regelung</u> - (heteroaxial orientation process) - An orientation process which results in unlike symmetry of the grain and megascopic fabrics.

<u>heterogenetisch geregeltes Gefüge</u> - (heterogenetic-oriented fabric) - Genetically different orientation in the same or different kinds of crystals in the same fabric.

<u>heterotaktische Regelung</u> - (heterotactic orientation process) - An orientation process which produces different symmetry for different minerals in the same fabric.

hkl-Fläche - (hkl-surface) p. 33.

h0l- Fläche - (h0l-surface) p. 33.

Höfe - "Bereiche" in a fabric in which the grains surround rigid elements, in whole or in part, and differ from the main fabric in some respect such as texture or composition.

homoachse Regelung - (homoaxial orientation process) - An orientation process which results in like symmetry of the grain and megascopic fabrics.

homogenetisch geregeltes Gefüge - (homogenetic-oriented fabric Genetically similar orientation in the same or different kinds of crystals in the same fabric.

homotaktische Regelung - (homotactic orientation process) - An orientation process which produces similar symmetry for different minerals.

Intergranular -(Intergranular film)

Interngefüge - (internal fabric, or 'si') p. 49.

Keimregelung - An orientation process which acts on sub-microscopic "seed" crystals.

kinetische Tektonik - p. 94.

Knickfalte (after Schmidt) Essentially the same as "Biegefalte"

Kornbauregelung - (lattice orientation process) p. 7.

Korngestaltregelung - (dimensional orientation process) p. 7.

Krümmung - The bent condition of any body or form previously straight.

laminare Strömung - (laminar flow) - If particles bounded by shear surfaces glide over each other along parallel lines, or on open curves oriented so that the gliding at every point has the same direction-sense as the main body of material (unverwickelte Kurven), the tectonic flowage is laminar.

Längsfäden - Fabric elements elongated parallel to the deformation plane 'ac'.

lineares Parallelgefüge, Linearstruktur - (linear-parallel fabric) - A fabric with parallel directions, rather than planes, predominating.

mechanisches Gefüge - (mechanical fabric) - A fabric resulting from mechanical action (as distinct from molecular).

mehrphasige B-tektonit - (multiple-phase B-tectonite) - A B-tectonite formed by two or more homoaxial deformation

mittelbare Teilbewegung - (indirect partial-movement) p. 48.

nachkristalline Deformation - (post-crystallization deformation) p. 49.

nichtrotationelle Regelung - (non-rotational orientation process) - A passive orientation process as a result of which the fabric elements are not rotated with respect to each other.

nichtrotationeller Strain - (non-rotational strain) p. 41.

Nichttektonit - (non-tectonite)

Okl-Fläche - (Okl-surface) p. 33.

parakristalline Deformation - (para-crystallization deformation) p. 49

parallelfasriges Wachstumsgefüge - (parallel-fibre growth fabric) - A fabric whose elements have grown from a plane blastetrix.

Parallelgefüge - (parallel fabric) - A fabric in which parallel planes or directions, or both, occur.

passive Regelung - (passive orientation process) p. 6.

Plan 1 - The common type of monoclinic strain as illustrated on p. 43.

Plan 2 - The triclinic type of strain as illustrated by crossed strains on p. 81.

Querfäden - Fabric elements elongated parallel to the tectonic axis 'b'.

radialstrahliges Wachstumsgefüge - (radial growth fabric) - A fabric whose elements grow from blastetrices which are not plane surfaces.

Regel - (orientation) p. 6.

Regelung - (orientation process) p. 6.

Restregel - (residual orientation) p. 72.

Richtungsgefüge - (direction fabric) - A fabric whose grain orientation is of the lattice type.

Richtungsregelung - Same as Kornbauregelung.

Riefung - Includes all the linear textures found in a fabric.

Rillen - The Riefung found on a Harnisch. By definition, parallel to 'a'.

R-Tektonit - (R-tectonite) - A B-tectonite which shows evidence of rotation either of single grains or of the whole fabric.

Scheinharnisch - A pseudo-"Harnisch".

Scherfalte - (shear fold) p. 101.

Scherflächen - According to Schmidt, Scherflächen are the circular sections of the strain ellipsoid. Most other investigators define them as surfaces in rocks parallel to which shearing has taken place

Schmelzgefüge - (igneous fabric) - A fabric whose elements are or were partly in the liquid state.

Schmelztektonit - (igneous tectonite) p. 110.

Schoppfalten - Sharply angular V-shaped folds.

s-Fläche - (s-surface) p. 63.

sperrige Kristallisation - A crystallization common in the knee of a fold in which the grains (particularly mica) are not in parallel dimensional arrangement to each other and to the s-surface, and apparently "lean" against each other.

Striemung - In tectonites, a visible linear texture parallel to the tectonic axis 'b'.

Strömungsfalte - A mixed type of shear and flexure fold. p. 104.

Teilbewegung - (partial-movement) p. 32.

Teilgefüge - (partial-fabric) - Groups of elements distributed at random in a fabric which have some common fabric property.

tektonische Fazies - (tectonic facies) - A secondary rock facies characterized by a 'durchbewegtes' fabric and by a schistophile mineral assemblage which adapts itself readily to the environment.

tektonisches Bügeln - (tectonic ironing) - A rock flowage in which unit A moves over unit A' by gliding in a boundary surface.

tektonisches Walzen - (tectonic rolling) - A rock flowage in which unit A is moved with respect to unit A' either by rotation of single elements or of the whole mass under consideration.

Tektonit - (tectonite) p. 32.

turbulente Strömung - (turbulent flow) - When particles bounded by s-surfaces glide over one another in curves whose direction-sense is opposite to the gliding direction of the main mass of material (verwickelte Kurven) the tectonic flowage of the mass is turbulent.

Ueberindividuum - (superindividual) p. 58.

Ueberprägung - If a fabric is modified by a second deformation without loss of all its earlier characteristics the whole is an Ueberprägung

Umfaltung - (re-folding) - The second of any two folding processes in which the shape of the original folds is changed.

Umformung - All mechanically ~~induced~~ change in the form of a structure.

Umkristallisation - A recrystallization which results in the formation of a new mineral species.

Umprägung - If a fabric is modified by a second deformation so that all its earlier characteristics are lost, the whole is an Umprägung.

Umregelung - The second of any two orienting processes, by which a new grain orientation is brought about in the fabric.

Umscherung - The second of any two shearing processes, as a result of which shear surfaces are developed in a different direction from those previously existing.

ungleichscharige Scherung (or Gleitung) - A "zweischarige Scherung" in which the two sets of shear surfaces are unequally developed.

unmittelbare Teilbewegung - (direct partial-movement) p. 48.

unverlagertes Interngefüge - (unrotated 'si') p. 49.

Verformung - essentially the same as Umformung.

verlagertes Interngefüge - (rotated 'si') p. 49.

vorkristalline Kristallisation - (pre-crystallization deformation) p. 49.

Wachstumsgefüge - (growth fabric) p. 116.

Wegsamkeit - The Wegsamkeit of a fabric is determined by the path of least resistance which the fabric offers

to growing elements, circulating solutions, etc.

wirtelige Symmetrie - (spheroidal symmetry) p. 34.

Zeilenstruktur - more or less synonymous with gneissic structure.

zweischarige Scherung (or Gleitung) - Shearing which occurs simultaneously parallel to both intersecting directions of slip during a deformation.

Literature

The following titles include only those papers to which direct reference is made in the text. A complete bibliography is to be found in references 2 and 36.

1. Leith, C.K. - Rock Cleavage - Bull. 239 U.S.G.S. (1905)
2. Sander, Bruno - Gefügekunde der Gesteine. Julius Springer, Vienna (1930)
3. Knopf, E.B. - Petrotectonics - Am. J. Sc. vol. 25 (1933)
4. Sander, Bruno - Petrofabrics and Orogenesis - Am. J. Sc. vol. 28 (1934)
5. Gilluly, James - Mineral Orientation in the Shuswap Terrane Am. J. Sc. vol. 28 (1934)
6. Cross, Iddings, Pirsson, Washington - A Classification of Igneous Rocks - Journ. Geol. vol. 10 (1902
7. Sander and Pernt - Zur petrographisch-tektonischen Analyse pt.1 Jahrb. Geol. B.A. Vienna, Bd. 74 (1923)
8. Schmidt, Walter - Gefügestatistik - Min. u. Petrog. Mitt. Bd. 38 (1925)
9. Drescher, F.K. - Ein grosses Universal Drehinstrument - Centr. f. Miner. Abt. A #5 (1932)

10. Korn, Doris - Ein deformiertes Flusspat-Kupferkiesgefüge - Neues Jahrb. f. Miner. Abt. A Bd. 66 (1933)

11. Korn, Doris - Zur Lagebestimmung opaker Erze - Neues Jahrb. f. Miner. Abt. A Bd. 67 (1933)

12. Sander and Sachs - Zur röntgenoptischen Gefügeanalyse von Gesteinen - Zt. f. Krist. Bd. 75 (1930)

13. Fairbairn, H.W. - A Petrofabric Analysis of Gypsum - In press.

14. Andreatta, C. - Analisi strutturale di rocce metamorfiche 1 - Periodico di Mineralogia Anno III (1932)

15. Urban, Karl - Gefügeanalytische Untersuchungen an Skapolith-führenden Gesteinen - Neues Jahrb. f. Miner. Abt. A Bd. 68 (1934)

16. Becker, G.F. - Current Theories of Slaty Cleavage - Am. J. Sc. vol. 24 (1907)

17. Mead, W.J. - Geologic Role of Dilatancy - Journ. Geol. vol 33. (1925)

18. Schmidt, Walter - Bewegungsspuren in Porphyroblasten kristalliner Schiefer - Sitzungsber. d. Kaiser. Akad. Wiss. in Wien, Math.-Naturw. Kl. Abt. 1 (1918)

19. Becke, F. - Struktur und Klüftung - Fortschr. d. Miner. Bd. 9 (1925)

20. Schwinner, Robert - Eine technologische Diagnose im Kristallin - Miner. u. Petr. Mitt. Bd. 42 (1932)

21. Sander, Bruno - Typisierung von deformierten Tonschierfern Zt. f. Krist. Bd. 89 (1934)

22. Leith, C.K. - Structural Geology - Henry Holt, New York (1923)

23. Schmidt, Walter - Tektonik und Verformungslehre - Gebrüder Bornträger, Berlin (1932)

24. Fairbairn, H.W. - Notes on Mechanics of Rock Foliation - In press.

25. Sander, Felkel, Drescher - Festigkeit und Gefügeregel am Beispiele eines Marmors - Neues Jahrb. f. Miner. Abt. A Bd. 59 (1929)

26. Sander and Schmidegg - Zur petrographisch-tektonischen Analyse III - Jahrb. Geol. B.A. Wien Bd. 76 (1926)

27. Becker, G.F. - Finite Homogeneous Strain, etc. Bull. Geol. Soc. Am. vol. 4 (1893)

28. Van Hise, C.R. - Deformation of Rocks - Journ. Geol. vol. 4 (1896)

29. Becke, F. - Über Kristallisationsschieferung und Piezokristallisation - Intern. Geol. Congr. (1906)

30. Johs, M. - Der Granitporphyr von Thal-Heiligenstein im Thüringer Wald - Min. u. Petro. Mitt. Bd. 43 (1933)

31. Maroschek, E.F. - Beiträge zur Kenntnis des Granites von Mauthausen - Miner. u. Petr. Mitt. Bd. 43 (1933)

32. Schmidegg, O. - Über geregelte Wachstumsgefüge - Jahrb. Geol. B.A. Wien Bd. 78 (1928)

33. Clar, E. - Die Gefügeregelung eines Bändermagnesits - Jahrb. d. Geol. B.A. Wien Bd. 81 (1931)

- Gefügestatistisches zur Metasomatose - Miner. u. Petr. Mitt. Bd. 44 (1932)

34. Ladurner, J. - Zur Kenntnis des Gefüges "gestreckter" Belemniten - Miner. u. Petr. Mitt. Bd. 44 (1933)

35. Christa, E. - Über Regelungserscheinungen im Schriftgranit - Verh. d. Phys.-Med. Gesellsch. zu Wurzburg Bd. 53 (1927)

- Über Myrmekit in zentralalpinen Gesteinen - Neues Jahrb. f. Miner. Abt. A. Bd. 57 (1928)

36. Sander, Bruno - Fortschritte der Gefügekunde der Gesteine usw. - Fortschr. d. Miner. Bd. 18 (1934)

Index